of LOX vessels and of pressure-relief valves (49 CFR 173.31 and 173.33) [1]. See 49 CFR 178.337 [1] for GOX and 49 CFR 178.338 [1] for LOX tankage testing.

Transportation Emergencies

Initial Actions

The first concern in a transportation emergency shall be to prevent death or injury. In an incident or emergency, try to get the vehicle off the road if possible, preferably to an open location that is off an asphalt road or parking lot. Shut off the tractor-trailer electrical system. Post warning lights and signs and keep people at least 152 m (500 ft) away for GOX or 800 m (1/2 mile) away for LOX. Contact authorities and obtain help:

CHEMTREC (800-424-9300) (worldwide 202-483-7616)

Emergency Actions

Emergency actions to combat leaks and fires involving oxygen tractor-trailers include pulling the vehicle into the least hazardous area and turning the ignition off. For fires originating near the engine, use a fire extinguisher; for tire fires, use water or chemical fire extinguishers or both. Tires may reignite 20 to 30 min after the initial fire has been extinguished, so the driver should not leave the scene until the tire temperature is lowered sufficiently. Also, the driver should not leave the scene until the fire has been completely extinguished and the burning materials cooled.

Aid should be requested from the nearest fire or police department or both. On the highway, the environment in which a fire and subsequent damage may occur is difficult to control. An incident may occur at any time and at any place along the route. A controlled release of oxygen from the trailer through venting should take into account all possible ignition sources, vapor dispersion, population exposure, and general safe operations. Flares normally used for highway vehicular incident identification should not be used in close proximity to upset or damage LOX tanks.

References

[1] CFR Title 49, *Transportation, Code of Federal Regulations*, Parts 171–180, Sections 171.8, 172.101, 172.700, 173.31, 173.33, 173.34, 173.115, 173.302, 173.306, 173.315, 173.316, 173.318, 173.320, 173.600, 177.840, 178.36, 178.337, 178.338.

[2] CFR Title 29, *Occupational Safety and Health Standards, Code of Federal Regulations*, Part 1910, Sections 94(d), 104, 114, 115, 252(a), and 252(f).

APPENDIX A

Chemical and Physical Properties of Oxygen

Oxygen, in both the gaseous and liquid states, is a powerful oxidizer that vigorously supports combustion.

The molecular weight of oxygen, O_2, is 31.9988 on the C^{12} scale, and its atomic weight is 15.9994 [A1]. Oxygen was the base used for chemical atomic weights, being assigned the atomic weight 16.000, until 1961 when the International Union of Pure and Applied Chemistry adopted carbon 12 as the new basis [A2,A3].

Oxygen has eight isotopes. There are three naturally occurring stable isotopes of oxygen; these have atomic mass numbers of 16, 17, and 18 [A2 − A4]. The naturally occurring isotopes of oxygen are difficult to separate; therefore, property data are generally obtained from naturally occurring oxygen, which has a concentration in the ratio of 10 000:4:20 for the three isotopes of atomic mass numbers 16, 17, and 18 [A2]. Also, the data are most generally given for diatomic, molecular oxygen, O_2 [A2]. The metastable molecule, O_3 (ozone), is not addressed in this manual.

Gaseous oxygen (GOX) is colorless, transparent, odorless, and tasteless. High-purity liquid oxygen (LOX) is light blue, odorless, and transparent.

GOX is about 1.1 times as heavy as air (specific gravity = 1.105). LOX is slightly more dense than water (specific gravity = 1.14).

LOX is a cryogenic liquid and boils vigorously at ambient pressure. It is chemically stable, is not shock sensitive, and will

TABLE A-1—Properties of oxygen at standard (STP) and normal (NTP) conditions [A1].

Properties	STP	NTP
Temperature, K (°F)	273.15 (32)	293.15 (68)
Pressure (absolute), kPa (psi)	101.325 (14.696)	101.325 (14.696)
Density, kg/m^3 (lb$_m$/ft^3)	1.429 (0.0892)	1.331 (0.0831)
Compressibility factor (PV/RT)	0.9990	0.9992
Specific heat		
At constant pressure (C_p), J/g·K (Btu/lb$_m$·°R)	0.9166 (0.2191)	0.9188 (0.2196)
At constant volume (C_v), J/g·K (Btu/lb$_m$·°R)	0.6550 (0.1566)	0.6575 (0.1572)
Specific heat ratio (C_p/C_v)	1.40	1.40
Enthalpy, J/g (Btu/lb$_m$)	248.06 (106.72)	266.41 (114.62)
Internal energy, J/g (Btu/lb$_m$)	177.16 (76.216)	190.30 (81.871)
Entropy, J/g·K (Btu/lb$_m$·°R)	6.325 (1.512)	6.391 (1.527)
Velocity of sound, m/s (ft/s)	315 (1034)	326 (1070)
Viscosity, mPa·s (lb/ft·s)	19.24 (0.01924)	20.36 (0.02036)
Thermal conductivity, mW/m·K (Btu/ft·h·°R)	24.28 (1.293×10^{-5})	25.75 (1.368×10^{-5})
Dielectric constant	1.00053	1.00049
Equivalent volume/volume liquid at NBP	798.4	857.1

not decompose. Most common solvents are solid at LOX temperatures, 54.4 to 90.2 K (−361.8 to −297.4°F).

Oxygen is not ordinarily considered a toxic gas. However, lung damage may result if the oxygen concentration in the atmosphere exceeds 60 vol% [A4]. Roth [A5], in reviewing the literature on oxygen toxicity, notes that the respiratory tract is adversely affected by oxygen at pressures to 2 atm; the central nervous system is adversely affected at higher pressures [A4, A5]. The prolonged exposure to pure oxygen at 1 atm may result in bronchitis, pneumonia, and lung collapse [A4,A5]. More information is located in the "Health" section of Chapter 1.

A selection of thermophysical properties of oxygen is given in Tables A-1 through A-4. Properties at standard conditions (STP and NTP) are given in Table A-1, at the critical point (CP) in Table A-2, at the normal boiling point (NBP)†[1] in Table A-3, and at the triple point (TP) in Table A-4.

TABLE A-2—Fixed point properties of oxygen at its critical point [A1].

Property	Value
Temperature, K (°F)	154.576 (–181.4)
Pressure (absolute), kPa (psi)	5042.7 (731.4)
Density, kg/m³ (lb_m/ft^3)	436.1 (27.288)
Compressibility factor (PV/RT)	0.2879
Heat of fusion and vaporization, J/g (Btu/lb_m)	0
Specific heat	
At saturation (C_s), J/g·K (Btu/lb_m·°R)	Very large
At constant pressure (C_p), J/g·K (Btu/lb_m·°R)	Very large
At constant volume (C_v), J/g·K (Btu/lb_m·°R)	1.209 (0.289)[a]
Specific heat ratio (C_p/C_v)	Large
Enthalpy, J/g (Btu/lb_m)	32.257 (13.88)[a]
Internal energy, J/g (Btu/lb_m)	20.70 (8.904)
Entropy, J/g·K (Btu/lb_m·°R)	4.2008 (1.004)
Velocity of sound, m/s (ft/s)	164 (538)
Viscosity, mPa·s (lb_m/ft·s)	31 (2.083 × 10^{-5})[a]
Thermal conductivity, mW/m·K (Btu/ft·h·°F)	Unavailable
Dielectric constant	1.17082
Surface tension, N/m (lb_f/ft)	0
Equivalent volume/volume liquid at NBP	2.2616

[a] Estimate.

PARAMAGNETISM

LOX is slightly magnetic in contrast with other cryogens, which are nonmagnetic [A3]. Its outstanding difference from most other cryogenic fluids is its strong paramagnetism [A2]. It is sufficiently paramagnetic to be attracted by a hand-held magnet [A6]. The paramagnetic susceptibility of LOX is 1.003 at its NBP [A3].

Solubility

LOX is completely miscible with liquid nitrogen and liquid fluorine. Methane is highly soluble in LOX, light hydrocarbons are usually soluble, and acetylene is soluble only to approximately 4 ppm. Contaminants in LOX may be in solution if they are present in quantities less than the solubility limit [A6]. Most solid hydrocarbons are less dense than LOX and will tend to float on the liquid surface [A6]. They may give evidence of their presence by forming a ring of solid material around the interior wall of the container near the liquid surface [A7]. The solubility of several hydrocarbons in LOX, as well as their lower flammability limits, is given in Table A-5.

Oxygen is soluble in water, and the quantity that may be dissolved decreases as the temperature of the water increases. The solubility of oxygen in water (vol/vol) is 4.89 % at 273 K (32°F), 3.16% at 298 K (77°F), 2.46% at 323 K (122°F), and 2.30 % at 373 K (212°F) [A8].

TABLE A-3—Fixed point properties of oxygen at its normal boiling point (NBP) [A1].

Properties	Liquid	Vapor
Temperature, K (°F)	90.180 (–297.3)	90.180 (–297.3)
Pressure (absolute), kPa (psi)	101.325 (14.696)	101.325 (14.696)
Density, kg/m³ (lb_m/ft^3)	1140.7 (71.215)	4.477 (0.2795)
Compressibility factor (PV/RT)	0.00379	0.9662
Heat of vaporization, J/g (Btu/lb_m)	212.89 (91.589)	
Specific heat		
At saturation (C_s), J/g·K (Btu/lb_m·°R)	1.692 (0.4044)	–1.663 (–0.397)
At constant pressure (C_p), J/g·K (Btu/lb_m·°R)	1.696 (0.4054)	0.9616 (0.2298)
At constant volume (C_v), J/g·K (Btu/lb_m·°R)	0.9263 (0.2214)	0.6650 (0.159)
Specific heat ratio (C_p/C_v)	1.832	1.447
Enthalpy, J/g (Btu/lb_m)	–133.45 (–57.412)	79.439 (34.176)
Internal energy, J/g (Btu/lb_m)	–133.54 (–57.450)	56.798 (24.436)
Entropy, J/g·K (Btu/lb_m·°R)	2.943 (0.7034)	5.3027 (1.2674)
Velocity of sound, m/s (ft/s)	903 (2963)	178 (584)
Viscosity, mPa·s (lb_m/ft·s)	195.8 (1.316 × 10^{-4})	6.85 (4.603 × 10^{-6})
Thermal conductivity, mW/m·K (Btu/ft·h·°R)	151.5 (0.08759)	8.544 (0.00494)
Dielectric constant	1.4870	1.00166
Surface tension, N/m (lb_f/ft)	0.0132 (0.0009045)	
Equivalent volume/volume liquid at NBP	1	254.9

[1] The † indicates a term defined in the Glossary (Appendix G).

TABLE A-4—Fixed point properties of oxygen at its triple point [A1].

Properties	Solid	Liquid	Vapor
Temperature, K (°F)	54.351 (–361.8)	54.351 (–361.8)	54.351 (–361.8)
Pressure (absolute), kPa (psi)	0.1517 (0.0220)	0.1517 (0.0220)	0.1517 (0.0220)
Density, kg/m^3 (lbm/ft^3)	1.359 (84.82)	1.306 (81.56)	0.01075 (0.000671)
Compressibility factor (PV/RT)		0.0000082	0.9986
Heat of fusion and vaporization, J/g (Btu/lbm)	13.90 (5.980)	242.55 (104.35)	. . .
Specific heat			
At saturation (C_s), J/g·K Btu/lbm·°R)	1.440 (0.3441)	1.666 (0.3982)	–3.397 (–0.8119)
At constant pressure (C_p), J/g·K (Btu/lbm·°R)		1.665 (0.3979)	0.9103 (0.2176)
At constant volume (C_v), J/g·K (Btu/lbm·°R)		1.114 (0.2663)	0.6503 (0.1554)
Specific heat ratio (C_p/C_v)		1.494	1.400
Enthalpy, J/g (Btu/lb$_m$)	–207.33 (–89.197)	–193.43 (–83.217)	49.120 (21.132)
Internal energy, J/g (Btu/lb$_m$)	–207.33 (–89.197)	–193.43 (–83.127)	35.000 (15.058)
Entropy, J/g·K (Btu/lb$_m$·°R)	1.841 (0.4401)	2.097 (0.5013)	6.5484 (1.565)
Velocity of sound, m/s (ft/s)	. . .	1.159 (3.803)	141 (463)
Viscosity, mPa·s (lb$_m$/ft·s)	. . .	619.4 (4.162 x10^{-4})	3.914 (2.630 x 10^{-6})
Thermal conductivity, mW/m·K (Btu/ft·h·°R)	. . .	192.9 (0.1115)	4.826 (0.00279)
Dielectric constant	1.614 (estimated)	1.5687	1.000004
Surface tension, N/m (lb$_f$/ft)	. . .	0.02265 (0.00155)	. . .
Equivalent volume/volume liquid at NBP	0.8397	0.8732	106.068

TABLE A-5—Solubility limit and lower flammability limit of hydrocarbons soluble in LOX [A7].

Hydrocarbon	Solubility, mol·ppm	Lower Flammable Limit, mol·ppm
Methane	980 000	50 000
Ethane	215 000	30 000
Propane	50 000	21 200
Ethylene	27 500	27 500
Propylene	700	20 000
i-Butane	1 910	18 000
Butene-1	1 000	16 000
n-Butane	860	18 600
i-Butylene	135	18 000
n-Pentane	20	14 000
Acetylene	5	25 000
n-Hexane	2	11 800
n-Decane	0.6	7 700
Acetone	1.5	. . .
Methanol	12	. . .
Ethanol	15	. . .

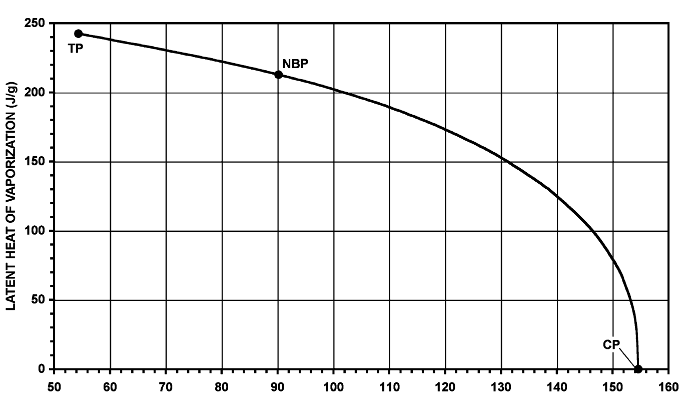

Fig. A-1—Latent heat of vaporization of liquid oxygen [A1].

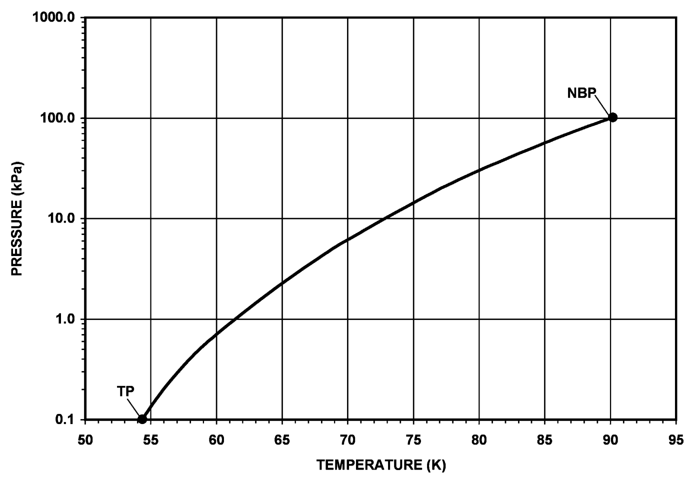

Fig. A-2—Vapor pressure of liquid oxygen from the TP to the NBP [A1].

HEAT OF VAPORIZATION

The latent heat of vaporization (the heat required to convert a unit mass of a fluid from the liquid state to the vapor state at constant pressure) of liquid oxygen is shown in Fig. A-1.

VAPOR PRESSURE

The vapor pressure (the P(T) of a liquid and its vapor in equilibrium) of liquid oxygen from the TP to the NBP is shown in Fig. A-2, and from the NBP to the CP in Fig. A-3.

SURFACE TENSION

The surface tension (the amount of work required to increase the surface area of a liquid by one unit of area) of liquid oxygen is shown in Fig. A-4. This property is defined only for the saturated liquid, not for the compressed fluid state.

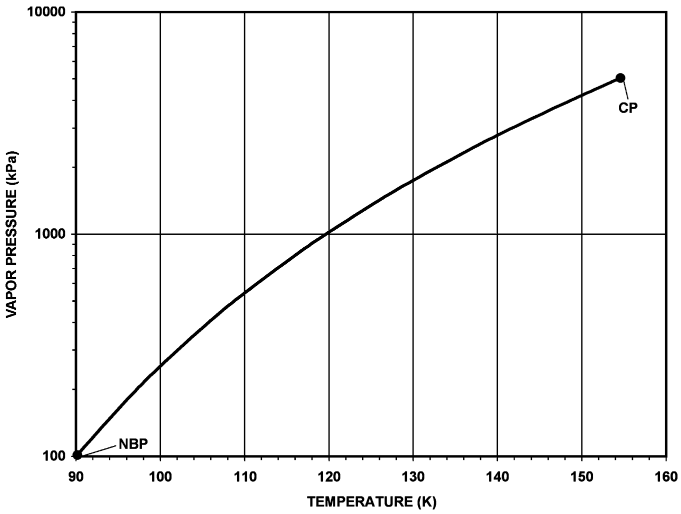

Fig. A-3—Vapor pressure of liquid oxygen from the NBP to the CP [A1].

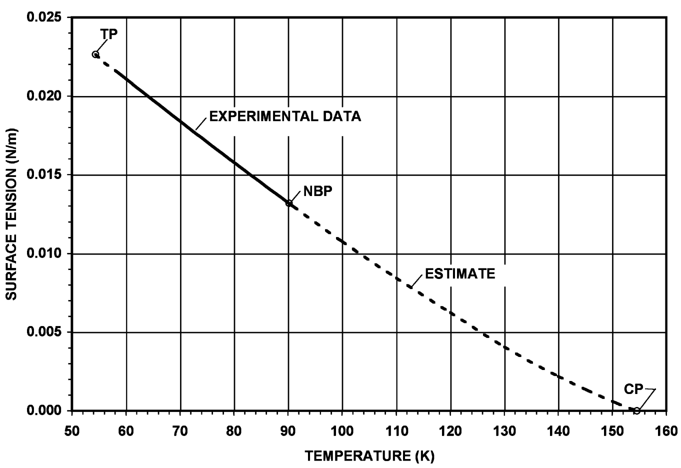

Fig. A-4—Surface tension of liquid oxygen [A1].

JOULE-THOMSON EFFECT

The Joule-Thomson effect is defined as the temperature change that occurs when a gas expands, through a restricted orifice, from a higher pressure to a lower pressure without exchanging heat, without gaining kinetic energy, and without performing work during the expansion process. This is a constant enthalpy (isenthalpic) process. In practice, this pressure change usually occurs at a valve. The change in temperature can be either positive or negative. A temperature increase will occur if the gas is expanded at a temperature and pressure condition that is outside the temperature and pressure conditions that define the Joule-Thomson inversion curve for the gas. A temperature decrease will occur if the gas is expanded at a temperature and pressure condition that is inside the Joule-Thomson inversion curve. The Joule-Thomson inversion curve for oxygen is shown in Fig. A-5. The oxygen Joule-Thomson inversion curve is a compilation of experimental and estimated data from Ref [A1]. Also shown in Fig. A-5 are four curves that show the isenthalpic expansion of oxygen from various initial conditions.

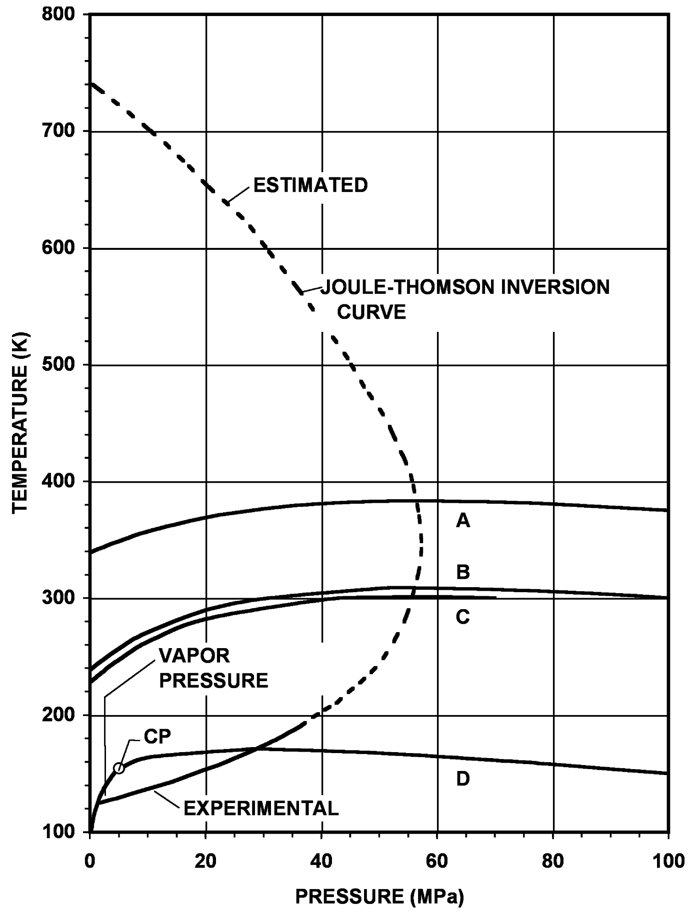

Fig. A-5—Joule-Thomson inversion curve for oxygen. Curves A-D show the isenthalpic expansion of oxygen from the following initial temperature and pressure conditions: Curve A—375 K, 100 MPa; Curve B—300 K, 100 MPa; Curve C—300 K, 70 MPa; Curve D—150 K, 100 MPa. CP = Critical Point.

TABLE A-6—Joule-Thomson coefficients for some selected temperature-pressure conditions.

Temperature (K)	Pressure (MPa)	J-T Coefficient (K/MPa)
100	20.3	–0.33555
	15	0.085459
	20.3	–0.04935
150	35	–0.22411
	70	–0.36151
	100	–0.40356
	15	1.9609
	20.3	0.96718
200	35	0.10706
	70	–0.28805
	100	–0.38088
	15	1.6934
	20.3	1.3323
300	35	0.54234
	70	–0.15410
	100	–0.33254
	15	1.1218
375	35	0.43555
	70	–0.13831
	100	–0.32447
	15	0.96873
400	35	0.38187
	70	–0.14423
	100	–0.32626

The Joule-Thomson coefficient is the derivative of the change in temperature as a result of a change in pressure at constant enthalpy. The Joule-Thomson coefficient is the slope of the isenthalpic lines, such as Curves A through D of Fig. A-5. The Joule-Thomson coefficient is zero at the Joule-Thomson inversion curve; that is, the Joule-Thomson inversion curve is the loci of the points where the Joule-Thomson coefficient is zero and the curve is at a maximum. The Joule-Thomson coefficients for some selected temperature and pressure conditions are given in Table A-6.

References

[A1] NASA, *ASRDI Oxygen Technology Survey*, *Vol. 1, Thermophysical Properties*, NASA SP-3071, H. M. Roder and L. A. Weber, Eds., National Aeronautics and Space Administration, Washington, DC, 1972.
[A2] Scott, R. B., *Cryogenic Engineering*, Met-Chem Research, Boulder, CO, 1988.
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[A4] Zabetakis, M. G., *Safety with Cryogenic Fluids*, Plenum Press, New York, 1967.
[A5] Roth, E. M., "Space-Cabin Atmospheres," in *Oxygen Toxicity, Part I*, NASA SP-47, U.S. Government Printing Office, Washington, DC, 1964.
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[A7] Edeskuty, F. J. and Stewart, W. F., *Safety in Handling of Cryogenic Fluids*, Plenum Press, New York, 1996.
[A8] Weast, R. C., Ed., *Handbook of Chemistry and Physics*, 56th Edition, CRC Press, Cleveland, Ohio, 1975.

APPENDIX B

Physical Properties of Engineering Materials

The mechanical and thermal properties–and, in some cases, other properties such as electrical, magnetic, and optical–of materials used in oxygen systems are important. The purpose of this section is to provide a brief introduction to the mechanical and thermal properties of some materials commonly used in oxygen systems, as well as to the properties and behavior of materials at cryogenic temperatures, such as the temperature of liquid oxygen (LOX). There are several significant phenomena that can appear at cryogenic temperatures, such as a ductile-brittle transition, that must be considered when selecting materials for LOX and cold gaseous oxygen (GOX) service.

Generally, the strength of a material at room temperature, or higher temperature if necessary for operational requirements, should be accounted for in the design of cryogenic equipment, although material strength generally tends to increase as its temperature is lowered. This recommendation is based on the recognition that the equipment must also operate at room temperature (or higher), and that temperature gradients are possible within the equipment, especially during cooldown or warmup.

There are many variables in a material and in its loading; consequently, material property values that are given in this guideline document should not be considered as approved design values. Approved design values may be obtained, for example, from the *ASME Boiler and Pressure Code* (for materials used in a pressure vessel) and from ANSI/ASME B31.3 for pressure piping. Representative allowable stress values for some materials from ANSI/ASME B31.3 are given in Table B-1.

TABLE B-1—Minimum temperatures and basic allowable stresses in tension for selected metals.[a]

Metal and/or Alloy[b]	Metal Form[c]	Minimum Temperature[d] K (°F)	Specified Minimum Tensile Strength MPa (ksi)	Specified Minimum Yield Strength MPa (ksi)	Basic Allowable Stress[e] MPa (ksi)
Aluminum alloy					
1100-0, B241	Pipe and tube	4.2 (–452)	75.8 (11)	20.7 (3)	13.8 (2.0)
3003-0, B241	Pipe and tube	4.2 (–452)	96.5 (14)	34.5 (5)	22.8 (3.3)
5083-0, B241	Pipe and tube	4.2 (–452)	268.9 (39)	110.3 (16)	73.8 (10.7)
6061-T6, B241	Pipe and tube	4.2 (–452)	262.0 (38)	241.3 (35)	87.6 (12.7)
Copper and copper alloy					
Cu pipe, B42, annealed	Pipe and tube	4.2 (–452)	206.8 (30)	62.1 (9)	41.4 (6.0)
Red brass pipe	Pipe and tube	4.2 (–452)	275.8 (40)	82.7 (12)	55.2 (8.0)
70Cu-30Ni, B466	Pipe and tube	4.2 (–452)	344.7 (50)	124.1 (18)	82.7 (12.0)
Nickel and nickel alloy					
Ni, B161	Pipe and tube	74.8 (–325)	379.2 (55)	103.4 (15)	68.9 (10.0)
Ni-Cu, B165	Pipe and tube	74.8 (–325)	482.6 (70)	193.1 (28)	128.9 (18.7)
Ni-Cr-Fe, B167	Pipe and tube	74.8 (–325)	551.6 (80)	206.8 (30)	137.9 (20.0)
Steel, carbon					
A285 Grade C, A524	Pipe and tube	244 (–20)	379.2 (55)	206.8 (30)	126.2 (18.3)
A442 Grade 50, A672	Pipe and tube	–[f]	413.7 (60)	220.6 (32)	137.9 (20.0)
Steel, low and intermediate alloy					
3.5 Ni, A333	Pipe and tube	172 (–150)	448.2 (65)	241.3 (35)	149.6 (21.7)
5 Ni, A645	plate	103 (–275)	655.0 (95)	448.2 (65)	218.6 (31.7)
9 Ni, A333	Pipe and tube	77 (–320)	689.5 (100)	517.1 (75)	218.6 (31.7)
Steel, stainless, ferritic					
405 (12Cr-Al), A240	Plate and sheet	244 (–20)	413.7 (60)	172.4 (25)	115.1 (16.7)
430 (17Cr), A240	Plate and sheet	244 (–20)	448.2 (65)	206.8 (30)	137.9 (18.4)

Continued

TABLE B-1—Minimum temperatures and basic allowable stresses in tension for selected metals.[a] *(Contd)*

Metal and/or Alloy[b]	Metal Form[c]	Temperature[d] K (°F)	Tensile Strength MPa (ksi)	Yield Strength MPa (ksi)	Allowable Stress[e] MPa (ksi)
Steel, stainless, martensitic					
410 (13Cr), A240	Plate and sheet	244 (–20)	448.2 (65)	206.8 (30)	126.9 (18.4)
Steel, stainless, austenitic					
304	Pipe and tube	19.3 (–425)	517.1 (75)	206.8 (30)	137.9 (20.0)
304L	Pipe and tube	19.3 (–425)	482.6 (70)	172.4 (25)	115.1 (16.7)
310 (25Cr-20Ni)	Plate and sheet	74.8 (–325)	517.1 (75)	206.8 (30)	137.9 (20.0)
310S	Pipe and tube	74.8 (–325)	517.1 (75)	206.8 (30)	137.9 (20.0)
316	Pipe and tube	19.3 (–425)	517.1 (75)	206.8 (30)	137.9 (20.0)
316L (16Cr-12Ni-2Mo)	Plate and sheet	19.3 (–425)	482.6 (70)	172.4 (25)	115.1 (16.7)
316L	Pipe and tube	74.8 (–325)	482.6 (70)	172.4 (25)	115.1 (16.7)
321 (18Cr-10Ni-Ti)	Pipe and tube	74.8 (–325)	517.1 (75)	206.8 (30)	137.9 (20.0)
347 (18Cr-10Ni-Cb)	Plate and sheet	19.3 (–425)	517.1 (75)	206.8 (30)	137.9 (20.0)
347	Pipe and tube	19.3 (–425)	517.1 (75)	206.8 (30)	137.9 (20.0)
Titanium and titanium alloy					
Ti, B337	Pipe and tube	214 (–75)	241.3 (35)	172.4 (25)	80.7 (11.7)
Ti-0.2Pd, B337	Pipe and tube	214 (–75)	344.7 (50)	275.8 (40)	115.1 (16.7)

[a] ANSI/ASME B31.3 (1996).
[b] ANSI/ASME B31.3 should be consulted regarding grade and specifications for these materials.
[c] ANSI/ASME B31.3 should be consulted for special notes regarding restrictions on these materials.
[d] The minimum temperature shown is that design minimum temperature for which the material is normally suitable without impact testing other than that required by the material specification. However, the use of a material at a design minimum temperature below 244 K (–20°F) is established by rules in ANSI/ASME B31.3, including any necessary impact test requirements.
[e] Basic allowable stress in tension for the temperature range from the minimum temperature to 311 K (100°F).
[f] ANSI/ASME B31.3 should be consulted regarding the minimum temperature for this material.

TABLE B-2—Elastic properties of selected materials at room temperature, LOX temperature, and liquid hydrogen temperature.

Material	Temperature, K	Young's Modulus, GPa	Shear Modulus, GPa	Bulk Modulus, GPa	Poisson's Ratio
Aluminum alloys					
5083-0	300	71.6[a]	26.82[a]	71.56[a]	0.3334[a]
	90	79.9[a]	30.24[a]	74.06[a]	0.3203[a]
	20	80.8[a]	30.68[a]	74.23[a]	0.3184[a]
6061-T6	300	70.2[a]	26.36[a]	72.14[a]	0.3383[a]
	90	76.8[a]	29.03[a]	74.55[a]	0.3286[a]
	20	77.7[a]	29.22[a]	74.83[a]	0.3269[a]
Invar	300	152.5[a]	55.8[a]	110.9[a]	0.2843[a]
	90	140.1[a]	51.0[a]	114.1[a]	0.3052[a]
	20	141.5[a]	50.5[a]	124.1[a]	0.3183[a]
Stainless steels					
304	300	189.8[a]	73.5[a]	150.7[a]	0.2901[a]
	90	204.1[a]	79.7[a]	154.1[a]	0.2792[a]
	20	204.5[a]	80.4[a]	148.8[a]	0.2714[a]
310	300	183.7[a]	70.2[a]	159.2[a]	0.3074[a]
	90	197.0[a]	75.8[a]	162.6[a]	0.2983[a]
	20	198.8[a]	76.7[a]	162.3[a]	0.2958[a]
316	300	203.8[a]	78.5[a]	167.7[a]	0.2972[a]
	90	219.2[a]	85.3[a]	170.4[a]	0.2856[a]
	20	220.6[a]	86.0[a]	168.4[a]	0.2819[a]
Fluorocarbon resins					
Polytetrafluorethylene (Teflon)	300	0.55[b,c]	–	–	–
(PTFE or TFE)	90	3.10[b,c]	–	–	–
	20	4.27[b,c]	–	–	–
Polytetrafluorethylene copolymer	300	0.48[b,c]	–	–	–
hexafluoropropylene (FEP)	90	3.86[b,c]	–	–	–
	20	5.03[b,c]	–	–	–

[a] Ref. [B1].
[b] Unfilled resin.
[c] Ref. [B2].

TABLE B-3—Mechanical properties of selected materials at room temperature, LOX temperature, and liquid hydrogen temperature.

Material	Temperature, K	Yield Strength, MPa	Tensile Strength, MPa	Fatigue Strength[a], MPa
Aluminum alloys				
3003-0	300	40[c]	110[c]	–
	90	57[c]	217[c]	–
	20	69[c]	372[c]	–
5083-0	300	141[c]	310[c]	235[c]
	90	155[c]	407[c]	283[b,c]
	20	170[c]	520[c]	...
6061-T6	300	278[c]	310[c]	200
	90	320[c]	402[c]	337[b,c]
	20	350[c]	498[c]	383
Invar	300	280[c]	510[c]	–
	90	630[c]	905[c]	–
	20	800[c]	1040[c]	–
Stainless steels				
304	300	285[c]	640[c]	190[c]
	90	340[c]	1520[c]	–
	20	390[c]	1730[c]	–
304L	300	410[c]	600[c]	210[c]
	90	430[c]	1380[c]	210[b,c]
	20	540[c]	1730[c]	...
310	300	210[c]	550[c]	280[c]
	90	500[c]	1050[c]	520[b,c]
	20	680[c]	1260[c]	700[c,f]
316	300	230[c]	570[c]	–
	90	540[c]	1210[c]	–
	20	610[c]	1400[c]	–
Fluorocarbon resins				
Polytetrafluorethylene (Teflon) (PTFE or TFE)	300	11.7[d,e]	31.0[d,e]	–
	90	83.4[d,e]	95.1[d,e]	–
	20	122.7[d,e]	123.4[d,e]	–
Polytetrafluorethylene copolymer hexafluoropropylene (FEP)	300	13.8[d,e]	27.6[d,e]	–
	90	125.5[d,e]	117.9[d,e]	–
	20	163.4[d,e]	164.1[d,e]	–

[a] Axial fatigue strength at 10^6 cycles.
[b] At 77 K.
[c] Ref. [B1].
[d] Unfilled resin.
[e] Ref. [B2].
[f] At 4 K.

29CFR1910.104 and NFPA 50 specify that LOX storage containers shall be fabricated from materials meeting the impact test requirements of paragraph UG-84 of the *ASME Boiler and Pressure Code*, Section VIII.

29CFR1910.104 specifies that piping or tubing operating below 244 K (−20°F), shall be fabricated from materials meeting the impact test requirements of paragraph UG-84 of the *ASME Boiler and Pressure Code*, Section VIII. NFPA 50 specifies that piping or tubing operating below 244 K (−20°F) shall be fabricated from materials meeting the impact test requirements of ANSI/ASME B31.3.

The designation by a material supplier that a material is suitable for cryogenic service does not necessarily indicate that the material is suitable (from a mechanical viewpoint) for LOX service. For example, nickel steels with 3.5, 5, and 9 % nickel are listed as satisfactory for cryogenic service with the following minimum temperature limits:

190 K (−150°F) for 3.5 nickel steel,
129 K (−260°F) for 5 nickel steel, and
76 K (−323°F) for 9 nickel steel.

Thus, only the 9 nickel steel would be satisfactory for LOX service, assuming other requirements are met.

Tables B-2 (elastic properties), B-3 (mechanical properties), and B-4 (thermal properties) give some typical property values at room temperature (300 K), LOX temperature (90 K), and liquid hydrogen temperature (20 K) for some materials cryogenically suitable for LOX service.

Mechanical Properties

Mechanical properties, such as yield, tensile, impact strength, and notch insensitivity, are important to consider when selecting a structural material for use in LOX service. The material must have certain minimum values of these properties over the entire operational temperature range with appropriate consideration for nonoperational conditions, such as a fire. The material must be metallurgically stable so that phase changes in the crystalline structure do not occur with time or repeated thermal cycling.

The main categories of material behavior to be considered are (i) transition from ductile to brittle behavior as a

TABLE B-4—Thermal properties of selected materials at room temperature, LOX temperature, and liquid hydrogen temperature.

Material	Temperature, K	Thermal Conductivity, W/(m·K)	Specific Heat, J/(kg·K)	Instantaneous Thermal Expansion,[a] 1/K	Linear Thermal Expansion,[b] m/m
Aluminum alloys					
3003	300	175[d]	902[d,f]	23.2×10^{-6} [d,f]	$+16 \times 10^{-5}$ [d,f]
	90	142[d]	418[d]	6.1×10^{-6} [d]	-375×10^{-5} [d]
	20	58[d]	8.9[d,f]	0.2×10^{-6} [d,f]	-415×10^{-5} [d,f]
5083	300	118[d]	902[d,f]	23.2×10^{-6} [d,f]	$+16 \times 10^{-5}$ [d,f]
	90	61.6[d]	418[d]	6.1×10^{-6} [d]	-375×10^{-5} [d]
	20	17.2[d]	8.9[d,f]	0.2×10^{-6} [d,f]	-415×10^{-5} [d,f]
6061	300	180[j]	902[d,f]	23.2×10^{-6} [d,f]	$+16 \times 10^{-5}$ [d,f]
	90	...	418[d]	6.1×10^{-6} [d]	-375×10^{-5} [d]
	20	...	8.9[d,f]	0.2×10^{-6} [d,f]	-415×10^{-5} [d,f]
Invar	300	14[d]	...	1.2×10^{-6} [d]	0[d]
	90	7.0[d]	...	1.02×10^{-6} [d]	-184×10^{-5} [d]
	20	1.65[d]	11.8[d]	0[d]	-40×10^{-5} [d]
Stainless steels					
304	300	14.7[d]	500[j]	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	8.6[d]	...*	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	2.12[d]	12.7[d]*	0.5×10^{-6} [d]	-298×10^{-5} [d]
304L	300	14.7[d]	...	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	8.6[d]	...*	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	2.12[d]	11.8[d]*	0.5×10^{-6} [d]	-298×10^{-5} [d]
310	300	11.5[d]	475[d]	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	6.5[d]	225[d]	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	1.71[d]	11.6[d]	0.5×10^{-6} [d]	-298×10^{-5} [d]
316	300	14.7[d]	480[d]	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	8.6[d]	230[d]	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	2.12[d]	13.7[d]	0.5×10^{-6} [d]	-298×10^{-5} [d]
Fluorocarbon resins					
Polytetrafluorethylene (Teflon)	300	0.25[h]	1 010[c,f]	1.5×10^{-4} [e,g]	0[i]
(PTFE or TFE)	90	0.22[k]	350[f]	...	...
	20	0.13[h]	76[f]	...	$-2\,150 \times 10^{-5}$ [i]
Polytetrafluorethylene copolymer	300	0.20[h]	1 088[h]	...	0[i]
hexafluoropropylene (FEP)	90	...	...	...	...
	20	0.12[h]	...	...	$-1\,800 \times 10^{-5}$ [i]

[a] Instantaneous thermal expansion = $[(1/L)(dL/dT)]$, with units of "1/K."
[b] Linear thermal expansion = $[(L - L_{293})/L_{293}]$, with units of "m/m."
[c] At 280 K, not 300 K.
[d] Ref. [B1].
[e] At 295 K, not 300 K.
[f] Ref. [B3].
[g] Ref. [B4].
[h] Ref. [B5].
[i] Ref. [B6].
[j] Ref. [B7].
[k] Ref. [B8].
* These data points have been corrected since the initial printing.

function of temperature; (ii) modes of plastic deformation, particularly certain unconventional modes encountered at very low temperatures; and (iii) the effect of metallurgical instability and phase transformations in the crystalline structure on mechanical and elastic properties. Two thermal properties to be considered in the selection of a material for LOX service are low-temperature embrittlement and thermal contraction.

In general, lowering the temperature of a solid will increase its yield and tensile strength, hardness, and resistance to fatigue. A few materials undergo solid-solid transitions that may or may not be reversible, and such a transition can be accompanied by an abrupt change in mechanical properties. The low-temperature embrittlement of some steels and most plastics is an illustration of such a transition [B9].

The Charpy impact test is commonly used to determine the ductility of a material. The results of the Charpy impact test as a function of temperature for several materials are shown in Fig. B-1. The abrupt ductile-to-brittle transition of C1020 carbon steel at about 130 K is shown in Fig. B-1. This figure also shows the large decrease in the Charpy impact strength for 9 % nickel steel. These results indicate that these materials are unsatisfactory for use in LOX service. The Charpy impact strength for 304 stainless steel does not show a significant change, and it actually increases slightly as the temperature decreases. This indicates that 304 stainless steel can be used in LOX service. The Charpy impact strength of 2024-T6 aluminum is low, but does not change much as the temperature decreases, indicating that it can be used for LOX service with caution because of its low value.

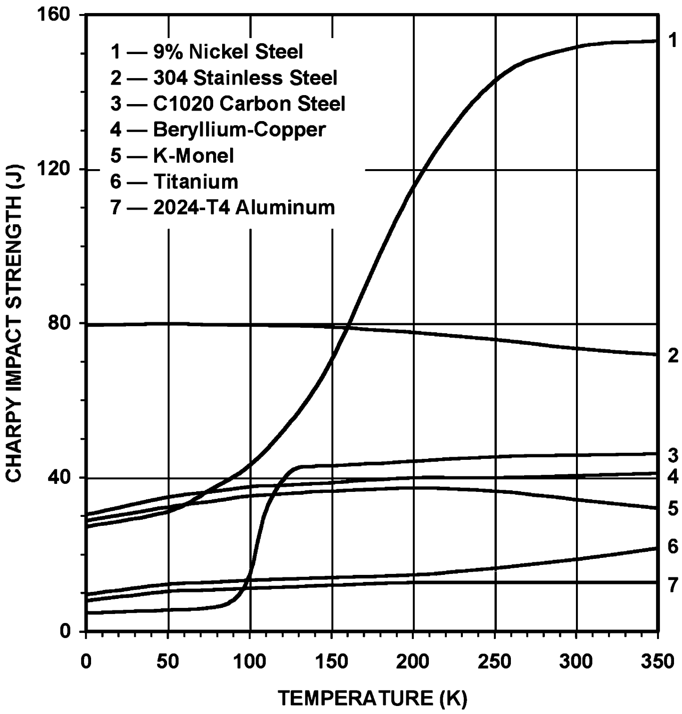

Fig. B-1—Charpy impact strength as a function of temperature for various materials [B10,B11].

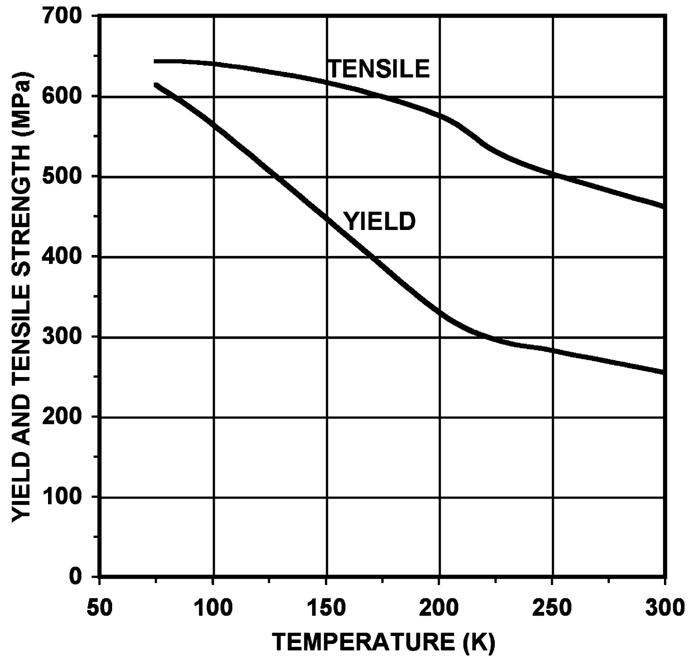

Fig. B-3—Yield and tensile strength of AISI 430 stainless steel as a function of temperature [B12].

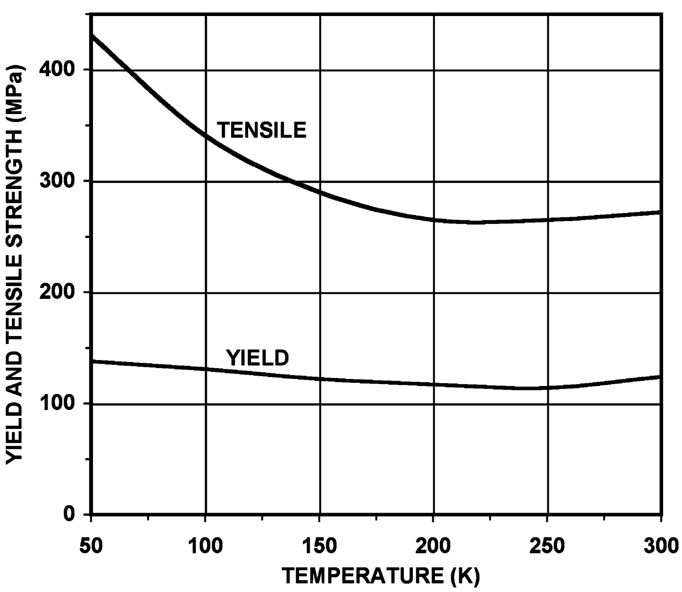

Fig. B-2—Yield and tensile strength of 5086 aluminum as a function of temperature [B12].

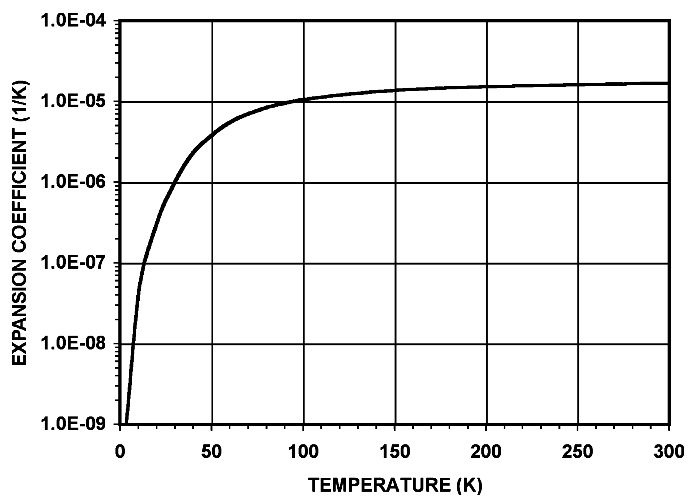

Fig. B-4—Thermal expansion coefficient [(1/*L*)(*dL*/*dT*)] of copper as a function of temperature [B3].

Another indication of the ductile or brittle behavior of a material is given by the relationship of the yield and tensile strength as a function of temperature. The yield and tensile strength of a material generally increase in decreasing temperature; but the rate of increase of the two properties gives an indication of the ductility change of the material. The yield and tensile strength of 5086 aluminum (a material considered satisfactory for LOX service) as a function of temperature are shown in Fig. B-2, which shows that tensile strength increases faster than the yield strength as the temperature decreases. The distance between the two curves provides an indication of the ductility of the material and for this material it remains ductile. In contrast, AISI 430 stainless steel becomes brittle as shown in Fig. B-3. The two curves of this steel approach each other at LOX temperature; therefore, it is considered unsatisfactory for use in LOX service.

Materials used in a LOX or cryogenic-temperature GOX system are subjected to cyclic loading (cooldown and warmup); therefore, only those that have been evaluated for suitable fatigue life should be used.

Thermal Properties

Materials generally have a positive thermal expansion coefficient, although there are a few exceptions to this over limited temperature spans. The span from ambient to LOX temperature is about 200 K (360°F). A temperature decrease of this magnitude will result in a significant thermal contraction in

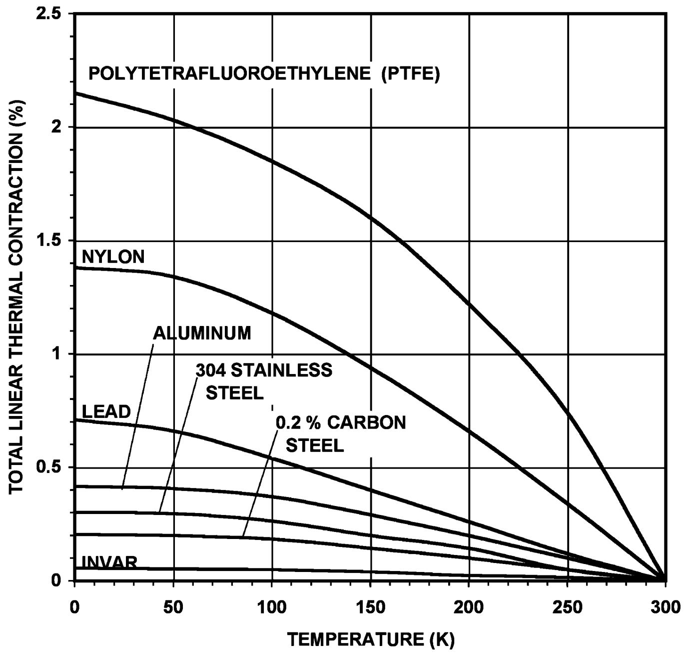

Fig. B-5—Total linear thermal contraction ($\Delta L/L_{300}$) as a function of temperature for several materials. This figure shows the total contraction at a given temperature as the temperature is lowered from 300 K (80°F) to the lower temperature [B13].

most materials, and this contraction must be accommodated in the use of the material in LOX service. The thermal expansion coefficient itself is a function of temperature. This is shown in Fig. B-4 for copper.

The total integrated thermal contraction from room temperature (300 K) to lower temperatures for several materials is shown in Fig. B-5, which shows that a thermal contraction of about 0.3 % in iron-based alloys, about 0.4 % in aluminum, and well over 1 % in many plastics occurs in cooling from room temperature to LOX temperature.

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APPENDIX C

Pressure Vessels—Testing, Inspection, and Recertification

GENERAL

Pressure vessels require testing, inspection, and qualification when installed, and they require periodic recertification while in service. Refer to Chapter 5 for details on pressure vessel design for oxygen service.

For the purposes of this appendix, the term "pressure vessel" may refer to any of the following:

1. ASME code pressure vessels.
2. NASA flight-weight pressure vessels. These do not meet ASME code. They typically have safety factors†[1] between 1.10 and 1.35.
3. NASA medium-weight pressure vessels. These do not meet ASME code, are nonflight, and have safety factors between 1.35 and 4.00.
4. DOT, API vessels, etc. These typically have safety factors between 1.5 and 4.0.
5. Compressed gas cylinders meeting the requirements of 49 CFR [C1].

Inspection and testing methods for establishing the suitability and safety of oxygen vessels, pressure vessels, piping, and equipment are included in industrial guidelines such as *Tentative Standard Insulated Tank Truck Specification* (CGA 341); "Pressure Vessels," *ASME Boiler and Pressure Vessel Code* (Section VIII) and "Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators," *ASME Boiler and Pressure Vessel Code* (Section IX); and "Process Piping" (ANSI/ASME B31.3).

The performance and design requirements of the system and its components should be verified by testing and analysis. Testing within off-limit ranges should be considered for evaluating limited design margins, single-point failures, and any uncertainties in the design criteria. Such testing should be performed in accordance with applicable codes. Before installation in a system, pressure vessels, piping, valves, flexible hoses, and pumping equipment should be pressure-qualification (proof) tested to ensure they can withstand internal test pressures higher than design operating pressures.

If repairs or additions are made after the proof tests, the affected piping or equipment must be retested. Equipment not to be subjected to the pressure test should be either

[1] The † indicates a term defined in the Glossary (Appendix G).

disconnected from the piping or isolated by blind flanges, caps, or other means during the test.

Cleanliness should be verified at system and component operating levels. Initial testing may be performed with clean inert fluids, and acceptance tests may be done with clean, oil-free nitrogen. Life tests, however, should be conducted with oxygen.

TESTING

Qualification and Acceptance Testing

Initial qualification tests to verify system integrity should not exceed the system's maximum allowable working pressure (MAWP)†. While the MAWP is held in the system, the test should be monitored from a remote location. After testing is completed, the components that have not previously been qualified for oxygen service should be re-evaluated for flow and functional capabilities. They should be disassembled and inspected after testing.

Pressure Testing

All oxygen containers and systems must be pressure tested according to the requirements of the authority having jurisdiction. Hydrostatic testing is recommended as a relatively safer and more reliable method of system testing than pneumatic pressure testing. However, because of the energy stored, hydrostatic testing should still be considered hazardous [C2]. Construction materials for the liquid oxygen (LOX) container and its attachments and the finished tank should be inspected as required by applicable codes. The liquid container should be subjected to either a hydrostatic or a proof test.

Note: Hydrostatic testing should be completed before-cleaning (Chapter 6).

Hydrostatic and pneumatic tests should be performed per the requirements of applicable codes for pressure vessels and ANSI/ASME B31.3 for piping and tubing. Pneumatic tests should be approved by the authority having jurisdiction.

Performance Testing

Performance testing of specification vessels authorized to transport oxygen is specified in various parts and subparts of 49CFR [C1]. The information given here is intended as an introduction to the performance testing required, and should not be considered as a complete coverage of such requirements. This information is based primarily on the requirements associated with Specification MC-338 insulated cargo tank vehicle [49CFR178.338].

General Requirements

A specification cargo tank motor vehicle shall not be filled or offered for transport if the prescribed periodic retest or reinspection under Subpart E of Part 180 of Subchapter C–Hazardous Materials Regulations is past due [49CFR173.33(a)(3)].

Holding Time

"Holding Time" and the holding time test that is required for a Specification MC-338 tank are described in 49CFR178.338-9. "Holding time" is the time, as determined by testing, that will elapse from loading until the pressure of the contents, under equilibrium conditions, reaches the level of the lowest pressure control valve or pressure relief valve setting [49CFR178.338-9].

The test to determine holding time must be performed by charging the tank with a cryogenic liquid having a boiling point, at a pressure of one atmosphere, absolute, no lower than the design service temperature of the tank. The tank must be charged to its maximum permitted filling density with that liquid and stabilized to the lowest practical pressure, which must be equal to or less than the pressure to be used for loading. The cargo tank together with its contents must then be exposed to ambient temperature. The tank pressure and ambient temperature must be recorded at 3-h intervals until the pressure level of the contents reaches the set-to-discharge pressure of the pressure control valve or pressure relief valve with the lowest setting. This total time lapse in hours represents the measured holding time at the actual average ambient temperature. This measured holding time for the test cryogenic liquid must be adjusted to an equivalent holding time for each cryogenic liquid that is to be identified on or adjacent to the specification plate, at an average ambient temperature of 85°F. This is the rated holding time (RHT). The marked rated holding time (MRHT) displayed on or adjacent to the specification plate (see 49CFR178.338-18(c)(10)) may not exceed this RHT. [49CFR178.338-9]

An optional test regimen that may be used is as follows [49CFR178.338-9].

1. If more than one cargo tank is made to the same design, only one cargo tank must be subjected to the full holding time test at the time of manufacture. However, each subsequent cargo tank made to the same design must be performance tested during its first trip. The holding time determined in this test may not be less than 90 % of the marked rated holding time. This test must be performed in accordance with 49CFR173.318(g)(3) and 49CFR177.840(h) of this subchapter, regardless of the classification of the cryogenic liquid.
2. The term "same design" as used in this section of 49CFR means cargo tanks made to the same design type [49CFR178.320(a)].
3. For a cargo tank used in nonflammable cryogenic liquid service, in place of the holding time tests described previously, the MRHT may be determined as follows:
   a. While the cargo tank is stationary, the heat transfer rate must be determined by measuring the normal evaporation rate of the test cryogenic liquid (preferably the lading, where feasible) maintained at approximately one atmosphere. The calculated heat transfer rate must be determined from:

$$q = [n(\Delta h)(85 - t_1)] / [t_s - t_f]$$

where

q = calculated heat transfer rate to cargo tank with lading, Btu/h.

n = normal evaporation rate, which is the rate of evaporation, determined by the test of a test cryogenic liquid in a cargo tank maintained at a pressure of approximately one atmosphere, absolute, lb/h.

Δh = latent heat of vaporization of test fluid at test pressure, Btu/lb.

t_s = average temperature of outer shell during test, °F.

t_1 = equilibrium temperature of lading at maximum loading pressure, °F.

t_f = equilibrium temperature of test fluid at one atmosphere, °F.

b. The RHT must be calculated as follows:

$$RHT = [(U_2 - U_1)\ W]/q$$

where

RHT = rated holding time, in hours

U_1 and U_2 = internal energy for the combined liquid and vapor lading at the pressure offered for transportation, and the set pressure of the applicable pressure control valve or pressure relief valve, respectively, Btu/lb.

W = total weight of the combined liquid and vapor lading in the cargo tank, pounds.

q = calculated heat transfer rate to cargo tank with lading, Btu/h.

c. The MRHT_h (see 49CFR178.338−18(b)(9)) may not exceed the RHT.

A specification plate that shall be installed on the Specification MC-338 insulated cargo tank shall contain the information specified by 49CFR178.338-18(c). The specified information includes the marked rated holding time for at least one cryogenic liquid, in hours, and the name of that cryogenic liquid (MRHT_h, name of cryogenic liquid). Marked rated holding marking for additional cryogenic liquids may be displayed on or adjacent to the specification plate [49CFR178.338-9].

Each cargo tank motor vehicle used to transport a flammable† cryogenic liquid must be examined after each shipment to determine its actual holding time [49CFR173.318(g)(3)]. (Note: as stated previously, 49CFR178.338-9 applies this to all cryogenic liquids although "flammable-cryogenic liquid" is specified here.) The record required by 49CFR177.840(h) may be used for this determination. If the examination indicates that the actual holding time of the cargo tank, after adjustment to reflect an average ambient temperature of 85°F, is less than 90 % of the MRHT for the cryogenic liquid marked on the specification plate or adjacent thereto (see 49CFR178.338−18(b)), the tank may not be refilled with any flammable cryogenic liquid until it is restored to its marked rated holding time value or it is remarked with the actual marked rated holding time determined by this examination. If the name of the flammable cryogenic liquid that was transported and its marked rated holding time are not displayed on or adjacent to the specification plate, this requirement may be met by deriving the MRHT of the cargo tank for that flammable cryogenic liquid and comparing that derived MRHT with the actual holding time after adjustment.

The driver of a motor vehicle transporting a Division 2.1 (flammable gas) material that is a cryogenic liquid in a package exceeding 450 L (119 gallons) of water capacity shall avoid unnecessary delays during transportation. If unforeseen conditions cause an excessive pressure rise, the driver shall manually vent the tank at a remote and safe location. For each shipment, the driver shall make a written record of the cargo tank pressure and ambient (outside) temperature [177.840(h)]:

1. At the start of each trip,
2. Immediately before and after any manual venting,
3. At least once every 5 h, and
4. At the destination point.

Each cargo tank used to transport a flammable cryogenic liquid must be examined after each shipment to determine its actual holding time (see 49CFR173.318(g)(3)). [49CFR180.405]

Leak Test

Each cargo tank must be tested for leaks in accordance with 49CFR180.407(c). [49CFR180.407(h)] The leakage test must include testing product piping with all valves and accessories in place and operative, except that any venting devices set to discharge at less than the leakage test pressure must be removed or rendered inoperative during the test. All internal or external self-closing stop valves must be tested for leak tightness. Each cargo tank of a multi-cargo tank motor vehicle must be tested with adjacent cargo tanks empty and at atmospheric pressure. Test pressure must be maintained for at least 5 min. Cargo tanks in liquefied compressed gas service must be externally inspected for leaks during the leakage test. Suitable safeguards must be provided to protect personnel should a failure occur. Cargo tanks may be leakage tested with hazardous materials contained in the cargo tank during the test. Leakage test pressure must be no less than 80 % of MAWP marked on the specification plate except as follows [49CFR180.407(h)(1)]:

1. A cargo tank with an MAWP of 690 kPa (100 psig) or more may be leakage tested at its maximum normal operating pressure provided it is in dedicated service or services; or
2. An operator of a Specification MC-330 or MC-331 cargo tank, and a nonspecification cargo tank authorized under 49CFR173.315(k), equipped with a meter may check leak tightness of the internal self-closing stop valve by conducting a meter creep test. (See Appendix B to 49CFR180.)
3. A nonspecification cargo tank required by 49CFR173.8(d) to be leakage tested must be tested at not less than 16.6 kPa (2.4 psig), or as specified in 49CFR180.407(h)(2).

The results of the leakage test must be recorded as specified in 49CFR180.417(b) [49CFR180.407(h)(5)].

A cargo tank that fails to retain leakage test pressure may not be returned to service as a specification cargo tank, except under conditions specified in 49CFR180.411(d). [49CFR180.407(h)(3)]

Weld Testing

Unless the welded joints on the inner container of a LOX vessel are fully radiographed, all welds in or on the shell and heads, both inside and outside, should be tested by the magnetic particle method, the fluorescent dye penetrant method, or the ultrasonic testing method (*ASME Boiler and Pressure Vessel Code*, Section VIII; also see "Inspection" in this appendix). All cracks and other rejectable defects shall be repaired according to the repair procedures prescribed in the code under which the tank was built. The welder and the welding procedure should be qualified in accordance with *ASME Boiler and Pressure Vessel Code*, Section IX.

The authority having jurisdiction is responsible for the welding done by personnel within his/her jurisdiction and shall conduct the required qualification tests of the welding procedures and the welders or welding operators. Contractors are responsible for welding done by their personnel. A supplier shall not accept a performance qualification made by a welder or a welding operator for another supplier without the authorized inspector's specific approval. If approval is given, acceptance is limited to performance qualification on piping and the same or equivalent procedures must be used, wherein the essential variables are within the limits set forth in *ASME Boiler and Pressure Vessel Code*, Section IX. A performance qualification must be renewed as required by the *ASME Boiler and Pressure Vessel Code*, Section IX.

Testing Aerospace (Flight-Weight) Pressure Vessels

NASA Aerospace Pressure Vessel Safety Standard [C3] includes standards for using fracture control techniques to design, fabricate, test, and operate aerospace pressure vessels. Where technically possible, each pressure vessel should be designed to accommodate pressure qualification and verification testing. Tests should be performed to confirm the design, manufacturing processes, and service life. Qualification tests must be conducted on flight-quality (Class III) hardware. All aerospace pressure vessels must be subjected to an acceptance pressure qualification test, such as described in MIL-STD-1522 [C4].

INSPECTION

Comprehensive inspection and control are required of all materials and components to be used in LOX and gaseous oxygen (GOX) piping installations. A quality control program should be established that will satisfy all requirements established by the authority having jurisdiction and construction code requirements for all piping, components, materials, and test equipment. Material identification and certification are required for all piping and components used in fabrication and assemblies subjected to LOX and GOX operating conditions. No substitutions for the materials and components specified are permitted, except where the substitution retains code compliance and has written approval.

Required inspections of the piping, storage, and system components should be made according to methods specified by the authority having jurisdiction. Personnel performing inspections shall be qualified.

Before and during installation, piping and components should be examined for the integrity of seals and other means provided to maintain the special cleanliness requirements for LOX and GOX.

All controls and protective equipment used in the test procedure including pressure-limiting devices, regulators, controllers, relief valves, and other safety devices should be tested to determine that they are in good mechanical condition, have adequate capacity, and will not introduce contaminants.

The flexible hoses used for oxygen transfer should be hydrostatic-tested before initial use and recertified by visual inspection at least every 5 years. The hydrostatic test pressure and date to which the flexible hose can be used should be permanently imprinted on an attached tag. Flexible hoses should be secured in accordance with specifications of the authority having jurisdiction. Hoses that are determined to be unserviceable shall be turned in and destroyed to prevent further use.

The following are common inspection methods. Applicable codes will provide specific requirements.

1. Visual safety examination to verify dimensions, joint preparation, alignment, welding or joining, supports, assembly, and erection.
2. Magnetic particle examination to detect cracks and other surface defects in ferromagnetic materials. The examination should be performed according to applicable codes.
3. Liquid penetrant examination to detect cracks and other surface defects in all types of metals. The examination should be performed according to applicable codes.
4. Radiographic examination as required by engineering design specifications established by the authority having jurisdiction:
   - Random radiography.
   - 100 % radiography according to the method outlined in applicable codes; high-pressure oxygen systems require 100 % radiography.
   - Ultrasonic examination of the material (including welded joints) for internal discontinuities and thickness. The examination should be according to applicable codes and is recommended for use on highly stressed weld joints.

In-Service Inspection and Recertification

Ground-Based Pressure Vessels and Systems

Inspection and recertification of ground-based pressure vessels should be according to policy and procedures established by the authority having jurisdiction. Each component within the system is identified and placed into one of the following categories: pressure vessels, tanks, vacuum vessels, piping and piping system components, and others: 49CFR173.33(a)(3); ANSI/ASME B31.3; *ASME Boiler and Pressure Vessel Code*; Refs [C1, C5].

Recertification periods and intervening periods of inspection should be established for the components, based on variations in energy level with modifications to consider cyclic duty, corrosion, and location.

Aerospace (Flight-Weight) Vessels

Inspection and recertification of aerospace vessels should be according to Ref [C4].

Fracture mechanics theory and test data should be used to establish proof-test conditions. The proof-test conditions should account for significant factors that could influence service life. Post-proof-test inspection is mandatory where the proof test does not provide, by direct demonstration, assurance of satisfactory performance over the specified service life. The fracture control plan should include required inspection intervals, periodic verification tests, and environmental conditioning for physical and corrosion protection [C6,C7].

RECORDS

Test records should be kept on file for each system and piping installation. These records should include:

1. The test data and identification of the system, component, and piping tested.
2. The test method (e.g., hydrostatic, pneumatic, sensitive leak test).
3. The test fluid, the test pressure, the test temperature, and the hold time at maximum test pressure.
4. The locations, types, and causes of failures and leaks in components and welded joints; the types of repair; and data on retest.
5. Written approval by the assigned safety/design engineer.
6. Nondestructive evaluation data.

Records should also be kept concerning the cleaning procedures used. At a minimum, records should specify the cleanliness level and what specification was used.

References

[C1] CFR Title 49, *Transportation*, Code of Federal Regulations.

[C2] Roth, E. M., *Space-Cabin Atmospheres, Part I*, NASA SP-47, 1964, p. 13.

[C3] NSS/HP-1740.1, *NASA Aerospace Pressure Vessel Safety Standard*, NASA Technical Memorandum, NASA TM-81074, NASA, 1974.

[C4] MIL-STD-1522, *Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems, Military Standard*, United States Air Force, Washington, DC, 1986.

[C5] NHB 8060.1B, *Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments That Support Combustion*, NASA TM-84066, NASA, Office of Safety and Mission Quality, 1981.

[C6] McHenry, H. I., "Advances in Cryogenic Engineering," *Fracture Mechanics and Its Application to Cryogenic Structures*, Vol. 22, K. D. Timmerhaus, R. P. Reed, and A. F. Clark, Eds., Plenum Press, New York, 1975, pp. 9–26.

[C7] Stuhrke, W. F. and Carpenter, J. L., Jr., *Fracture Toughness Testing Data: A Technology Survey*, OR-13432, Martin Marietta Aerospace, NASA Contract NAS3-17640, NASA CR-134752, 1975.

APPENDIX D

Codes, Regulations, and Guidelines Listing

Increased safety of personnel and facilities requires compliance with existing regulations as well as adherence to accepted standards and guidelines. Regulations are directives by official bodies authorized to create safety requirements enforceable by political jurisdiction. The regulations are mandatory. On the federal level, these include regulations by the Department of Transportation (DOT), the Environmental Protection Agency (EPA), and the Occupational Safety and Health Administration (OSHA). State and local officials may also issue regulations. The general process for making regulations is as follows:

1. Proposed regulations are usually published along with a description of the issues. Comments are sought and reviewed and consideration is given to oral arguments made by interested parties.
2. Recommendations of other government agencies and of interested parties are also considered.
3. When final regulations are published, provisions are made for interested parties to petition the officials to amend or repeal these regulations.
4. Most regulations originate with the federal government and are contained in the Code of Federal Regulations (CFR). They are introduced by DOT, OSHA, or the U.S. Coast Guard. Transportation: Code of Federal Regulations (49 CFR) designates the rule-making and enforcement bodies of the DOT. Some current federal regulations that pertain to interstate shipping of LOX (cryogenic fluids) and GOX (compressed gases) are listed in Table D-1.

Various industrial and governmental organizations have published standards and guidelines for the construction of facilities and for safe procedures to be followed in the various phases of production, handling, and use of LOX. Many of these published guidelines have been adapted by regulatory bodies such as the DOT, OSHA, the Federal Aviation Administration, the Coast Guard, and the Office of Hazardous Materials.

Rules and guidelines are the technical information and safe practices and procedures developed by organizations (or

TABLE D-1—Selected federal regulations for shipping oxidizers interstate.

Summary of DOT Hazardous Materials Regulations	
Highway and railroad	
CFR Title 49 172, 173, 174, 175, 176, 177	Hazardous materials regulations; labeling shipping classification
CFR Title 49 173.302	Charging cylinders with nonliquified compressed gases
CFR Title 49 177.840, 177.848, 177.859	Loading and unloading requirements: procedures in accidents (includes procedures for leakage)
CFR Title 49 178.337	Specifications for MC-331 cargo tanks: design, construction, testing, and certification
Portable tanks	
49 CFR 178.245, 178.246, 179.247, 173.315, 173.32	Information on design, loading of compressed gases, and safety relief requirements
Tank cars	
49 CFR 179	Specifications for tank cars
49 CFR 173.304, 173.314	Allowable filling densities, labeling for liquids and gases, and unloading requirements
49 CFR 178.337, 177.824	Cargo tank specifications and general design requirements for transformation of compressed gases
49 CFR 179.104, 179.105	Special tank-car tank requirements
49 CFR 179.200 to 179.400	Safety relief valve requirements: includes Appendix A of the AAR Specifications for Tank Cars (AAR 204W)
Cylinder design	
49 CFR 178	Specifications for cylinders
49 CFR 173.301 173.302, 178.36, 178.37, 178.45	General information on cylinder specifications, manifolding, filling, pressure limits, and safety relief
Pipelines	
49 CFR 191 to 195	Minimum standards for inspection, testing, and maintenance of natural gas and other gas pipelines; new standards published in 1977
Air transport	
14 CFR 103 Tariff 6D	Limitations of shipment by air: air-transport-restricted articles and regulations

Note: For changes in existing federal code for transportation of cryogenic fluids proposed by Hazardous Materials Regulations Board, see Federal Register Docket No. H.M. 115, Notice No. 74-3.

groups representing such organizations) for their own needs, such as NASA and the Los Alamos National Laboratory. These organizations assign technically qualified personnel (or committees) to evaluate hazards and to develop information, rules, and guidelines for minimizing operational risks.

Codes and standards are the consensus safety documents developed by nonprofit trade associations, professional societies, or standards-making and testing bodies that serve industrial, commercial, and public needs. Examples are the American National Standards Institute and the National Fire Protection Association. They are empowered to include advisory and mandatory provisions that may be adopted by authorized regulatory agencies.

Most of these guidelines and standards are not mandatory, except those from government organizations. Within NASA (for example), some controls are mandatory for NASA employees such as NPR 8715.3A [D1]. In addition, each NASA center has its own safety manuals, management instructions and other materials.

Numerous groups, societies, and associations are responsible for monitoring oxygen safety standards. These groups and their applicable documents follow.

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

- ANSI/ASQ Z1.4-2003, *Sampling Procedures and Tables for Inspection*
- ANSI B31.3, *Process Piping*
- ANSI B31.8, *American National Standard Code for Pressure Piping, Gas Transmission and Distribution Piping Systems*
- ANSI/NFPA 50, *Bulk Oxygen Systems at Consumer Sites*
- ANSI/NFPA 53, *Fire Hazards in Oxygen-Enriched Atmospheres*
- ANSI/SAE AIR 1176A, *Oxygen System and Component Cleaning and Packaging*
- ANSI/SAE AMS 3012, *Oxygen, Liquid Propellant Grade*
- ANSI/SAE AS 8010B, *Aviator's Breathing Oxygen Purity Standard*
- ANSI/SAE AS 1046B, *Minimum Standard for Portable Gaseous Oxygen Equipment*

AMERICAN PETROLEUM INSTITUTE (API)

- API 620, *Recommended Rules for Design and Construction of Large, Welded, Low-Pressure Storage Tanks*

AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME)

- *ASME Boiler and Pressure Vessel Code,* Sect. VIII, Div. 1 and 2, *Pressure Vessels*
- *ASME Boiler and Pressure Vessel Code,* Sect. IX, *Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*
- PTC 25.3-1976, *Safety and Relief Valves*

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

- G 63, *Guide for Evaluating Nonmetallic Materials for Oxygen Service*
- G 72, *Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment*
- G 74, *Test Method for Ignition Sensitivity of Materials to Gaseous Fluid Impact*
- G 86, *Standard Test Method for Determining Ignition Sensitivity of Materials through Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments*
- G 88, *Guide for Designing Systems for Oxygen Service*
- G 93, *Practice for Cleaning Methods for Material and Equipment Used in Oxygen-Enriched Environments*
- G 94, *Guide for Evaluating Metals for Oxygen Service*
- G 114, *Practice for Aging Oxygen-Service Materials Prior to Flammability Testing*
- G 120, *Practice for Determination of Soluble Residual Contamination in Materials and Components by Soxhlet Extraction*
- G 121, *Practice for Preparation of Contaminated Test Coupons for the Evaluation of Cleaning Agents*
- G 122, *Test Method for Evaluating the Effectiveness of Cleaning Agents*
- G 124, *Test Method for Determining the Combustion Behavior of Metallic Materials in Oxygen-Enriched Atmospheres*
- G 125, *Test Method for Measuring Liquid and Solid Material Fire Limits in Gaseous Oxidants*
- G 126, *Terminology Relating to the Compatibility and Sensitivity of Materials in Oxygen-Enriched Environments*
- G 127, *Guide for Selection of Cleaning Agents for Oxygen Systems*
- G 128, *Guide for Control of Hazards and Risks in Oxygen Enriched Systems*
- G 131, *Practice for Cleaning of Materials and Components by Ultrasonic Techniques*
- G 136, *Practice for Determination of Soluble Residual Contaminants in Materials by Ultrasonic Extraction*
- G 144, *Test Method for Determination of Residual Contamination of Materials and Components by Total Carbon Analysis Using a High-Temperature Combustion Analyzer*
- G 145, *Guide for Studying Fire Incidents in Oxygen Systems*
- G 175, *Test Method for Evaluating the Ignition Sensitivity and Fault Tolerance of Oxygen Regulators Used for Medical and Emergency Applications*
- D 2963, *Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index)*
- D 4809, *Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)*.

COMPRESSED GAS ASSOCIATION (CGA)

- AV-8, *Characteristics and Safe Handling of Cryogenic Liquid and Gaseous Oxygen*
- C-7, *Guide to the Preparation of Precautionary Labeling and Marking of Compressed Gas Containers*
- CGA-341, *Standard for Insulated Cargo Tank Specification for Nonflammable Cryogenic Liquids*
- G-4, *Oxygen*
- G-4.1, *Cleaning Equipment for Oxygen Service*
- G-4.3, *Commodity Specification for Oxygen*
- G-4.4, *Oxygen Pipeline Systems (EIGA Doc. 13/02)*
- G-4.5, *Commodity Specification for Oxygen Produced by Chemical Reaction*
- G-4.6, *Oxygen Compressor Installation and Operation Guide*
- G-4.7, *Installation Guide for Stationary, Electric-Motor-Driven, Centrifugal Liquid Oxygen Pumps*

- G-4.8, *Safe Use of Aluminum-Structured Packing for Oxygen Distillation (EIGA Doc. 701/04).*
- G-4.9, *Safe Use of Brazed Aluminum Heat Exchangers for Producing Pressurized Oxygen (EIGA Doc. 702/04)*
- O2-DIR, *2000 Directory of Cleaning Agents for Oxygen Service*
- P-1, *Safe Handling of Compressed Gases in Containers*
- P-14, *Accident Prevention in Oxygen-Rich and Oxygen-Deficient Atmospheres (superseded by P-39 and SB-2)*
- P-2.5, *Transfilling of High Pressure Gaseous Oxygen to be Used for Respiration*
- P-2.6, *Transfilling of Liquid Oxygen Used for Respiration*
- P-2.7, *Guide for the Safe Storage, Handling, and Use of Portable Liquid Oxygen Systems in Healthcare Facilities*
- P-8.1, *Safe Installation and Operation of PSA and Membrane Oxygen and Nitrogen Generators*
- P-8.2, *Guideline for Validation of Air Separation Unit and Cargo Tank Filling for Oxygen USP and Nitrogen NF*
- P-31, *Liquid Oxygen, Nitrogen, and Argon Cryogenic Tanker Loading System Guide*
- P-35, *Guidelines for Unloading Tankers of Cryogenic Oxygen, Nitrogen, and Argon*
- P-39, *Oxygen-Rich Atmospheres*
- PS-1, *CGA Position Statement on Odorizing Atmospheric Gases (Oxygen, Nitrogen, and Argon)*
- PS-13, *CGA Position Statement on Definition of a Threshold Oxygen-Mixture Concentration Requiring Special Cleaning of Equipment*
- PS-15, CGA *Position Statement on Toxicity Considerations of Nonmetallic Materials in Medical Oxygen Cylinder*
- PS-19, *CGA Position Statement on the Use of Oxygen and Acetylene Cylinders on a Cylinder Cart*
- S-1.1, *Pressure Relief Device Standards—Part 1—Cylinders for Compressed Gases*
- S-1.2, *Pressure Relief Device Standards—Part 2—Cargo and Portable Tanks for Compressed Gases*
- S-1.3, *Pressure Relief Device Standards—Part 3—Stationary Storage Containers for Compressed Gas*
- SB-2, *Oxygen-Deficient Atmospheres*
- SB-7, *Rupture of Oxygen Cylinders in the Offshore Marine Industry*
- SB-9, *Recommended Practice for the Outfitting and Operation of Vehicles Used in the Transportation and Transfilling of Liquid Oxygen to Be Used for Respiration*
- SB-23, *Liquid Oxygen Withdrawal from Healthcare Facilities' Bulk Systems*
- SB-31, *Hazards of Oxygen in the Health Care Environment*
- SP-E, *Safety Poster, Oxygen and Oil Don't Mix*
- TB-12, *Design Considerations for Nonmetallic Materials in High Pressure Oxygen Supply Systems*
- *Handbook of Compressed Gases*, Chapter 2: "Regulatory Authorities for Compressed Gases in United States and Canada"; and Appendix A, "Summary of Selected State Regulations and Codes Concerning Compressed Gases"

EUROPEAN INDUSTRIAL GASES ASSOCIATION (EIGA)

- Doc. 4/00, *Fire Hazards of Oxygen and Oxygen Enriched Atmospheres*
- Doc. 10/81, *Reciprocating Compressors for Oxygen Service. Code of Practice.*
- Doc. 11/82, *Code of Practice for the Design and Operation of Centrifugal Liquid Oxygen Pumps*
- Doc. 13/02, *Oxygen Pipeline Systems*
- Doc. 27/01, *Centrifugal Compressors for Oxygen Service. Code of Practice*
- Doc. 33/06, *Cleaning of Equipment for Oxygen Service: Guideline*.
- Doc. 87/02, *Conversion of Cryogenic Transport Tanks to Oxygen Service*
- Doc. 89/06, *Safe Use of Medical Oxygen Systems for Supply to Patients with Respiratory Disease*
- Doc. 98/03, *Safe Supply of Transportable Medical Liquid Oxygen Systems by Healthcare Service Providers*
- Doc. 104/03, *Safe Principles for Pressure Regulators for Medical Oxygen Cylinders*
- Doc. 127/04, *Bulk Liquid Oxygen, Nitrogen and Argon Storage Systems at Production Sites*
- Doc. 128/04, *Design and Operation of Vehicles Used in Medical Oxygen Homecare Deliveries*
- Doc. 701/06, *Safe Use of Aluminium-Structures Packing for Oxygen Distillation*
- Doc. 702/04, *Safe Use of Brazed Aluminium Heat Exchangers for Producing Pressurized Oxygene at sdafHeat*
- Doc. 705/06, *Installation Guide for Stationary, Electric-Motor-Driven, Centrifugal Liquid Oxygen Pumps*
- PP-14, *Definitions of Oxygen Enrichment/Deficiency Safety Criteria Used in IHC Member Associations*
- Info 15/00, *Safety Principles of High Pressure Oxygen Systems*
- Info 16/00, *Fire in Regulators for Oxygen in Industrial Service*
- NL 71/99, *Oxygen for Healthcare/CO_2 Cylinders with Quick-Opening Valves*
- NL 72/00, *Filters in Oxygen System/Excessive Pressure—Small Tanks*
- NL 73/00, *Oxygen Enrichment in Water/Silane Cylinder Safety*
- NL 79/04/E, *Hazards of Oxygen Enriched Atmospheres/ EIGA Campaign Highlighting the Hazards of Oxygen Enriched Atmospheres*
- PR 01/03, *Oxygen Deficiency Presentation*

FEDERAL GOVERNMENT

- 14 CFR 60–199, *Aeronautics and Space*
- 29 CFR 1910, *Occupational Safety and Health (OSHA)*
- 46 CFR 140–149, *Shipping*
- 49 CFR 101–180, *Transportation*
- Federal Motor Carrier Safety Regulations, *Federal Highway Administration*, Chapter 3 and Parts 390–397
- The Association of American Railroads, *Specifications for Tank Cars*
- IATA, *Air Transport Restricted Articles*

INSURING ASSOCIATIONS

- American Insurance Association
- Factory Mutual Organization
- Industrial Risk Insurers

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

- ISO 4589-1:1996, *Plastics—Determination of Burning Behaviour by Oxygen Index—Part 1: Guidance*
- ISO 4589-2:1996, *Plastics—Determination of Burning Behaviour by Oxygen Index—Part 2: Ambient-Temperature test*

- ISO 4589-3:1996, *Plastics—Determination of Burning Behaviour by Oxygen Index—Part 3: Elevated-Temperature Test*
- ISO 5175:1987, *Equipment used in gas welding, cutting and allied processes—Safety devices for fuel gases and oxygen or compressed air—General specifications, requirements and tests*
- ISO 8206:1991, *Acceptance tests for oxygen cutting machines—Reproducible accuracy—Operational characteristics*
- ISO 8359:1996, *Oxygen concentrators for medical use—Safety requirements*
- ISO 8775:1988, *Aerospace—Gaseous oxygen replenishment connection for use in fluid systems (new type)—Dimensions (Inch series)*
- ISO 11114-3:1997, *Transportable gas cylinders—Compatibility of cylinder and valve materials with gas contents—Part 3: Autogenous ignition test in oxygen atmosphere*
- ISO 14624-4:2003, *Space systems—Safety and compatibility of materials—Part 4: Determination of upward flammability of materials in pressurized gaseous oxygen or oxygen-enriched environments*
- ISO 14951-1:1999, *Space systems—Fluid characteristics—Part 1: Oxygen*
- ISO 15859-1:2004, *Space systems—Fluid characteristics, sampling and test methods—Part 1: Oxygen*
- ISO 17455:2005, *Plastics piping systems—Multilayer pipes—Determination of the oxygen permeability of the barrier pipe*
- ISO 20421-1:2006, *Cryogenic vessels—Large transportable vacuum-insulated vessels—Part 1: Design, fabrication, inspection and testing*
- ISO 20421-2:2005, *Cryogenic vessels—Large transportable vacuum-insulated vessels—Part 2: Operational requirement*
- ISO/DIS 21009-1, *Cryogenic vessels—Static vacuum-insulated vessels—Part 1: Design, fabrication, inspection and tests*
- ISO 21009-2:2006, *Cryogenic vessels—Static vacuum insulated vessels—Part 2: Operational requirements*
- ISO 21029-1:2004, *Cryogenic vessels—Transportable vacuum insulated vessels of not more than 1 000 litres volume—Part 1: Design, fabrication, inspection and tests*
- ISO 21029-2:2004, *Cryogenic vessels—Transportable vacuum insulated vessels of not more than 1 000 litres volume—Part 2: Operational requirements*
- ISO 23208:2005, *Cryogenic vessels—Cleanliness for cryogenic service*
- ISO 24431:2006, *Gas cylinders—Cylinders for compressed and liquefied gases (excluding acetylene)—Inspection at time of filling*

NATIONAL FIRE PROTECTION ASSOCIATION (NFPA)

- NFPA 50, *Standard for Bulk Oxygen Systems at Consumer Sites*
- NFPA 53, *Manual on Fire Hazards in Oxygen-Enriched Atmospheres*
- NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
- NFPA 68, *Explosion Venting*
- NFPA 69, *Explosion Prevention System*
- NFPA 70, *National Electric Code*
- NFPA 78, *Lightning Protection Code*
- NFPA 496, *Purged and Pressurized Enclosures for Electrical Equipment in Hazardous Locations*
- NFPA Volumes 1 and 2, *National Fire Codes*

OTHER ORGANIZATIONS (INCLUDING U.S. GOVERNMENT AGENCIES)

- Arthur D. Little, Inc. (ADL)
- Battelle Columbus Laboratories (BCL)
- Bureau of Mines (BM)
- Chemical Propulsion Information Agency (CPIA)
- Department of Defense (DoD)
- Department of Transportation (DOT)
  - Federal Aviation Administration (FAA)
  - Federal Highway Administration
  - Federal Railroad Administration
  - Hazardous Materials Regulation Board (HMRB)
  - Office of Pipeline Safety
  - Office of Hazardous Materials (OHM)
  - U.S. Coast Guard (USCG)
- National Aeronautics and Space Administration (NASA)
- National Bureau of Standards (NBS) (this organization is now the National Institute of Standards and Technology (NIST))
- University of California, Los Alamos National Laboratory (LANL)

PROFESSIONAL SOCIETIES

- American Industrial Hygiene Association (AIHA)
- American Institute of Chemical Engineers (AIChE)
- American Society of Heating, Refrigeration, and Air Conditioning Engineering (ASHRAE)
- Institute of Electrical and Electronic Engineering (IEEE)
- Instrument Society of America (ISA)

SOCIETY OF AUTOMOTIVE ENGINEERS

- SAE AIR 17IC, *Glossary of Technical and Physiological Terms Related to Aerospace Oxygen Systems*
- SAE AIR 505, *Oxygen Equipment, Provisioning and Use in High Altitude (to 40 000 Feet.) Commercial Transport Aircraft*
- SAE AIR 822A, *Oxygen Systems for General Aviation*
- SAE AIR 825B, *Oxygen Equipment for Aircraft*
- SAE AIR 847, *Oxygen Equipment for Commercial Transport Aircraft Which Fly Above 45 000 Feet*
- SAE AIR 1059A, *Transfilling and Maintenance of Oxygen Cylinders*
- SAE AIR 1069, *Crew Oxygen Requirements Up to a Maximum Altitude of 45 000 Feet*
- SAE AIR 1176A, *Oxygen System and Component Cleaning and Packaging*
- SAE AIR 1223, *Installation of Liquid Oxygen Systems in Civil Aircraft*
- SAE AIR 1389, *FAA Regulations Covering the Use of Oxygen in Aircraft*
- SAE AIR 1390, *Convenient Location of Oxygen Masks for Both the Crew and Passengers of Aircraft*
- SAE AIR 1392, *Oxygen System Maintenance Guide*
- SAE ARP 433, *Liquid Oxygen Quantity Instruments*
- SAE ARP 1109B, *Dynamic Testing Systems for Oxygen Breathing Equipment*
- SAE ARP 1320A, *Determination of Chlorine in Oxygen from Solid Chemical Oxygen Generators*
- SAE ARP 1398, *Testing of Oxygen Equipment*

- SAE ARP 1532A, *Aircraft Oxygen System Lines, Fabrication, Test and Installation*
- SAE AS 452A, *Oxygen Mask Assembly, Demand and Pressure Breathing Crew*
- SAE AS 861, *Minimum General Standards for Oxygen Systems*
- SAE AS 916B, *Oxygen Flow Indicators*
- SAE AS 1046B, *Minimum Standard for Portable Gaseous, Oxygen Equipment*
- SAE AS 1065, *Quality and Serviceability Requirements for Aircraft Cylinder Assemblies Charged with Aviator's Breathing Oxygen*
- SAE AS 1066A, *Minimum Standards Valve, for High Pressure, Oxygen Cylinder Shut Off, Manually Operated*
- SAE AS 1214A, *Minimum Standards for Valve, High Pressure Oxygen, Line Shut Off, Manually Operated*
- SAE AS 1224B, *Continuous Flow Aviation Oxygen Masks (for Non-Transport Category Aircraft)*
- SAE AS 1225A, *Oxygen System Fill/Check Valve*
- SAE AS 1248A, *Minimum Standard for Gaseous Oxygen Pressure Reducers*
- SAE AS 1303A, *Portable Chemical Oxygen*
- SAE AS 1304A, *Continuous Flow Chemical Oxygen Generators*
- SAE AS 8010C, *Aviator's Breathing Oxygen Purity Standard*
- SAE AS 8025, *Passenger Oxygen Mask*
- SAE AS 8026A, *Crewmember Demand Oxygen Mask for Transport Category Aircraft*
- SAE AS 8027, *Crew Member Oxygen Regulators, Demand*
- SAE AS 8047, *Performance Standard for Cabin Crew Portable Protective Breathing Equipment for Use During Aircraft Emergencies*

TECHNICAL AND TRADE GROUPS

- American Association of Railroads (AAR)
- American Gas Association (AGA)
- American Petroleum Institute (API)
- Manufacturers' Chemists Association (MCA)
- Manufacturers' Standardization Society (MSS)
- Manufacturers' Standardization Society of Valve and Fittings
- Industry (MSS)
- National Electrical Manufacturer's Association (NEMA)

TESTING STANDARDS AND SAFETY GROUPS

- National Safety Council
- Underwriters' Laboratories, Inc.

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APPENDIX E

Scaling Laws, Explosions, Blasts, and Fragments

SCALING LAWS

A comprehensive review of accidental explosions has been made [E1]. The review characterizes explosions by type, discusses the various scaling laws, and summarizes nonideal blast wave behavior and the mechanisms by which blast waves cause damage. Also see Refs [E2–E4].

The classical experimental work on blast waves has mainly used either high explosives or nuclear weapons to produce the waves. The intermediate- and far-field waves usually resemble those predicted from point-source theory quite closely, so either high explosives or nuclear explosions can be considered ideal.

A point-source blast wave is a blast wave conceptually produced by the instantaneous deposition of a fixed quantity of energy at an infinitesimal point in a uniform atmosphere. Essentially, a point-source wave propagating away from its origin creates three regions of interest. The first is the near-field wave in which pressures are so large that external pressure (or counterpressure) can be neglected. This region is followed by an intermediate region of extreme practical importance because the overpressure†[1] and impulse are sufficiently high to do significant damage. The intermediate region is followed in turn by a "far-field" region that yields to an analytical approximation such that the positive overpressure portion of the curve for large distances can be easily constructed from the overpressure time curve at one far-field position.

Scaling the properties of point-source blast waves is common practice and is subject to cube-root scaling (Sach's law) [E1,E3]. Theoretically, a given pressure will occur at a distance from an explosion that is proportional to the cube root of the energy yield. Full-scale tests have shown this relationship between distance and energy yield to hold over a wide range of explosive weights. According to this law, if d_1 is the distance from a reference explosion of W_1 (in pounds) at which a specified static overpressure or dynamic pressure is found, for any explosion of W (in pounds) these same pressures will occur at a distance d given by

$$d/d_1 = [W/W_1]^{1/3} \qquad \text{(E-1)}$$

Consequently, plots of overpressures for various weight of explosives can be superimposed on the curve for 0.45 kg (1 lb) of explosive if, instead of distance, the distance divided by the cube root of the weight is plotted against overpressure. This correlating parameter, $d/(W^{1/3})$, called "scaled distance," is used to simplify the presentation of the blast wave characteristics.

Cube-root scaling can also be applied to arrival time of the shock front, positive-phase duration, and impulse; the distances concerned also are scaled according to the cube-root law. The relationships can be expressed in the form

$$t/t_1 = d/d_1 = [W/W_1]^{1/3}$$
$$I/I_1 = d/d_1 = [W/W_1]^{1/3} \qquad \text{(E-2)}$$

where

t = Arrival time or positive time of duration.
t_1 = Arrival time or positive-phase duration for reference explosion.
I = Impulse.
I_1 = Impulse for the reference explosion W_1.
d = Distance from origin.
d_1 = Distance from origin for reference explosion W_1.

If W_1 is taken as 1 lb (0.45 kg), the various quantities are related as

$t = t_1 W^{1/3}$ at a distance $d = d_1 W^{1/3}$.
$I = I_1 W^{1/3}$ at a distance $d = d_1 W^{1/3}$.

However, no general laws exist for scaling blast waves from nonideal explosions because not all the physical parameters affecting such explosions are known. The general

[1] The † indicates a term defined in the Glossary (Appendix G).

concept of equivalence for a nonideal explosion is not well understood. Usually the near-field overpressures are much lower than those of a point-source explosion that produces the equivalent far-field overpressure, but it is not obvious exactly what the relationship between near-field and far-field behavior should be or how this relationship differs with the type of accidental explosion. It is also not obvious how to evaluate the blast damage of any particular type of accidental explosion or how much the damage depends on the type of explosion.

EXPLOSIONS

Explosions in Buildings

Explosions in buildings are of three main types. The severity of damage increases from Type 1 to Type 3.

1. *Type 1.* Some combustible material spills, resulting in a slow deflagration wave or flashback fire that causes a relatively slow pressure buildup in the building.
2. *Type 2.* A piece of equipment explodes, producing a blast wave inside the building that either damages the structure or is relieved by venting.
3. *Type 3.* A leak occurs and the combustible mixture that forms detonates.

In a detonation, the blast wave behavior and the damage patterns are determined primarily by the behavior of the detonation and are only modified by the confinement. For the previously discussed explosions, the degree of confinement or the bursting pressure of the vessel or building determines the nature of the blast wave and the damage patterns generated.

Tank Ruptures

A rupture followed by combustion is a very special type of explosion. It occurs when a tank of liquefied fuel under pressure is heated by an external fire until it vents and torches. For an explosion to occur, the heating of the venting tank must be sufficiently intense to cause the internal pressure to rise above the tank's bursting pressure, even with venting. This type of explosion has three distinct damage-producing effects:

1. A blast wave caused by internal pressure relief.
2. A fireball caused by subsequent massive burning of the tank's contents in the air.
3. Large fragments scattered for long distances because of the ductile nature of the tank's rupture and the rocketing of pieces by the pressure of the tank contents.

Because propellant explosions are not considered as point sources, the comparison between ideal and accidental explosions is inexact; the concept of TNT equivalence, which is widely used in safety studies, is also very inexact and may be quite misleading.

Recent studies show that no single TNT equivalent can be used to describe the blast generated by a rupturing pressure vessel. However, the blast pressures combined with the positive shock-wave durations yielded positive shock wave impulse values, whose impulse-distance relationship was similar in slope to that for TNT. For large, high-pressure vessels, the impulses from tank rupture and those for TNT equivalent are not significantly different quantitatively. A general comparison of blast and fragment parameters generated by tank rupture and an equivalent TNT charge showed that static (side-on) pressures were higher for TNT above 41 to 69 kPa (6 to 10 psi) and lower for TNT at pressures below these values. Peak reflected (face-on) tank pressures showed a similar relationship to face-on TNT pressures. Positive shock wave durations were longer for tank rupture than for TNT. Impulse values, both face-on and side-on, were similar for TNT and tank rupture. Damage, depending on distance, may be greater for tank rupture. Tank-rupture fragments were larger than would be expected from a cased TNT charge (all aforementioned information is from Ref [E5]).

Fragment velocities would be higher for a cased TNT charge than for tank rupture [E6, E7]. The term "strength" refers to several characteristics of a blast wave that relate to the wave's potential for causing damage. These characteristics are as follows [E8]:

1. *Side-on overpressure*. The overpressure in the blast wave, which would be observed were there no interaction between the blast and the structure.
2. *Duration*. After the wave front passes, the static pressure falls and actually drops slightly below atmospheric pressure. However, it is the duration of the positive phase (the time required to drop the peak overpressure to atmospheric pressure) that is of greatest significance in causing damage.
3. *Blast-wind velocity*. Behind the wave front the air moves at considerable speed in the same direction as the wave. For example, a peak overpressure of 34.5 kPa (5 psi) will be accompanied by a 72-m/s (236-ft/s) wind [E8].
4. *Stagnation overpressure*. The combined effects of side-on overpressure and the blast wind describe the load on the front face after the reflected shock has died out.
5. *Reflected overpressure*. If a blast wave strikes a surface (such as a wall) at normal incidence, the airflow will stop, and a shock wave will reflect backward from the surface. Behind the reflected shock, the surface will briefly be subjected to the peak reflected overpressure (sometimes called the face-on overpressure), which the instantaneous dynamic loads impose on the front face of the structure.
6. *Positive phase impulse*. The area under the positive phase of the side-on overpressure curve. Impulse has dimensions of force-time product and is obtained graphically given the side-on overpressure curve as a function of time.

Ground-Handling System Explosions

The hazards from accidental explosions in propellant ground-handling systems are similar in many respects to the hazards from such explosions in flight vehicles. These accidents cause damage by air-blast loading, fragment or appurtenance impact, radiation from fireballs, or fire from the ignition of combustible materials [E1,E3,E4,E9,E10].

Both flight and ground systems can fail by material fatigue caused by overstressing. However, many of the possible causes of flight vehicle explosions such as loss of thrust during launch, guidance system failure, or rupture of a bulkhead separating a fuel from an oxidizer, are inapplicable for ground-handling systems. Conversely, transportation accidents followed by explosions are not likely to occur in flight.

Because ground-handling systems have fewer weight constraints and therefore higher safety factors than do flight vehicles, the nature of the hazards is different. Also, the total energy stored in compressed gases or the total chemical energy stored in fuels and oxidants can be much greater than for many flight systems.

Many more accidental explosions involving fuels and compressed fluids have occurred in ground-handling systems than in flight vehicles. These include:

1. Simple pressure-vessel failure because of fatigue or flaw growth.

2. Vessel failure induced by impact during a transportation accident.
3. Vessel failure by overpressure because of overheating.
4. Vessel and pipeline failure by overpressure, corrosion, or erosion.
5. Fuel leakage followed by a vapor cloud explosion.

The workbooks and handbooks included in Refs. [E6] and [E9] provide methods for predicting blast and fragment characteristics and effects for a wide range of possible explosion accidents in ground and flight systems. The material in the workbooks allows estimation of:

1. Explosive energy yield or energy release.
2. Characteristics of blast pressure waves generated by spherical and nonspherical explosions.
3. Effects of pressure waves on certain classes of targets.
4. Characteristics of fragments generated by ground equipment explosions, including massive vessel parts that rocket.
5. Effects of fragment impact, including effects of fragment revetments on blast waves. Various safety factors are included in the prediction methods.

BLASTS

The primary source of blasts from accidental explosions in propellant ground handling and transportation systems is the rupture of compressed fuel or oxidizer cylinders, vessels, or lines. The various formulas for total energy release for compressed gas bursts are reviewed in Ref. [E7]. These include:

1. The explosive yield from compressed gas pressure burst

$$E = \frac{p_1 - p_a}{\gamma_1 - 1} V_1 \tag{E-3}$$

where

E = blast yield† (energy)
p_1 = initial absolute pressure in the vessel
p_a = absolute pressure of the outside atmosphere
γ_1 = ratio of specific heats for the gas in the vessel
V_1 = initial volume of the vessel before it bursts

2. An estimate based on isentropic expansion from initial burst pressure to atmospheric pressure:

$$E = \frac{p_1 V_1}{\gamma_1 - 1}\left(1 - \left(\frac{p_a}{p_1}\right)^{(\gamma_1 - 1)/\gamma_1}\right) \tag{E-4}$$

3. A lower limit on the energy released, for example by constant-pressure addition of energy to the explosion source region at a release rate so slow that it does not produce a blast wave

$$E = p_a(V_f - V_1) \tag{E-5}$$

where

V_f = the final volume occupied by the gas that was originally in the vessel.

The three equations [E-3 through E-5] are given in descending order of total blast energy. The blast yield is considered to lie between Eqs E-4 and E-5. Equation E-3 gives slightly higher values than does Eq E-4, but both are considered very conservative [E7].

The equations given for blast yields are based on the assumption that all the energy that can drive a blast wave does so, depending only on the energy release rate. For real vessels, some energy must be absorbed by the vessel as it fractures, both in the fracturing process itself and in accelerating the vessel fragments to their maximum velocity.

Methods for estimating the velocity and kinetic energy of the vessel fragments are provided in Ref [E7]. Also, the characteristics of blast waves from liquid propellant explosions and spherical gas vessel bursts and their similarities to and differences from waves from condensed high explosives such as TNT are reviewed in Ref [E7].

To estimate blast wave properties, dimensionless parameters are used [E7]. Prediction curves for scaled values of these parameters are given as functions of two dimensionless variables: $\bar{P}_1$ (dimensionless overpressure) and $\bar{R}$ (dimensionless distance). The properties of interest are: p_s (peak side-on overpressure); t_a (time of arrival of peak side-on overpressure); T (duration of the positive phase of the peak side-on overpressure; and I_s (the positive phase specific impulse). All blast parameters are plotted as nondimensional and are shown as functions (f_i) of the two dimensionless variables $\bar{P}_1$ and $\bar{R}$; that is,

$$f_i = f_1(\bar{P}_1, \bar{R}) \tag{E-6}$$

where

$$\bar{P}_1 = \frac{p_1}{p_a}\text{, and} \tag{E-7}$$

$$\bar{R} = \frac{R p_a^{1/3}}{E^{1/3}}. \tag{E-8}$$

Values of the following properties can be calculated from the scaled curves from plots of overpressure and impulse graphed as a function of the dimensionless scaled distance, $\bar{R}$:

$$\left.\begin{aligned} \bar{p}_s &= \frac{p_s}{p_a}, \\ \bar{t}_a &= \frac{t_a A_a p_a^{1/3}}{E^{1/3}}, \\ \bar{T} &= \frac{T A_a p_a^{1/3}}{E^{1/3}}, \text{ and} \\ \bar{I}_s &= \frac{I_s A_a}{p_a^{2/3} E^{1/3}}; \end{aligned}\right\} = f_1(\bar{p}_1, \bar{R}) \tag{E-9}$$

where

p_a = ambient absolute pressure (pressure of the atmosphere outside the vessel),
E = blast yield (internal energy in the sphere),
R = radius of the blast wave (standoff distance),
p_s = peak side-on overpressure,
t_a = time of arrival of peak side-on overpressure,
A_a = ambient sound velocity,
T = duration of positive phase of the peak side-on overpressure,
I_s = positive-phase specific impulse of peak side-on overpressure, and
p_1 = internal absolute pressure of the vessel.

Scaling laws for nonideal explosions are not known exactly now, but they can be easily developed once the physics of such explosions are well known. They will likely be variants on Sach's law [E1,E3]. Theoretical work and some test results suggest that at distances at which the absolute pressure levels are over approximately 103.4 kPa (15 psi) for liquid oxygen (LOX)–liquid hydrogen explosions, the TNT equivalence in terms of peak pressure is approximately 0.07; for absolute pressure levels from 101.4 to 0.69 kPa (14.7 to 0.1 psi), the TNT equivalence is approximately 1; and below 0.69 kPa (0.1 psi) it is approximately 2.0. Interpreting these numbers means that at an absolute pressure of 101.4 kPa (14.7 psi) and above, it takes approximately 6.5 kg (14.3 lb) of LOX and liquid hydrogen to generate the same pressure-distance relationship as does 0.45 kg (1 lb) of TNT; approximately 0.45 kg (1 lb) of LOX and liquid hydrogen at an absolute pressure of between 101.4 and 0.69 kPa (14.7 psi to 0.1 psi); and only 0.23 kg (0.5 lb) of LOX and liquid hydrogen at an absolute pressure of less than 0.69 kPa (0.1 psi). If blast wave characteristics can be defined for accidental explosions, correlation with damage effects on buildings, vehicles, humans, etc., can be made from existing methods and data in the literature [E3,E7,E9].

Fragmentation patterns from accidental explosions and the damaging effects of these fragments are difficult to predict. The blast waves produced by the explosion of liquid propellants that are accidentally mixed are usually unreproducible and difficult to model adequately. Extensive studies show that liquid-propellant explosions differ from TNT explosions in a number of ways, so the concept of TNT equivalence is far from exact.

FRAGMENTS

The fragments generated by bursting oxygen high-pressure gas or liquid vessels can vary widely in size and shape, depending on the total energy released, the release rate, and the pressure vessel design. A vessel that bursts because of a seam failure or crack propagation may generate only one fragment. This fragment can be propelled by the release of the contents. At the other extreme, a vessel whose contents explode can produce many small fragments.

In similar explosions, fewer fragments are generated in ground systems than in flight systems, primarily because of differences in pressure vessel materials and construction. Analytical predictions of fragment velocity distributions, fragmentation patterns, and free-flight ranges for lifting and rocketing fragments are given in Ref. E11.

Results of fragmentation studies providing fragment characteristics, mass, shape, and range as they relate to estimated blast yields of exploding liquid-propellant flight system tanks are included in Refs. [E1, E3, E6, E7, E9] and [E13]. Methods of determining yields of blast behavior are described in Refs. [E3, E7, E12], and [E13].

Methods for predicting velocities and ranges of fragments from bursting vessels are available. The fragment range information is based on data from various explosion sources. Data are included in Refs. [E1, E3, E9], and [E10].

The fragment range and mass distributions for various explosion sources are also included in Refs [E1, E3, E9], and [E10].

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APPENDIX F

Organizational Policies and Procedures, Project Management, and Reviews

INTRODUCTION

An organization involved in the use of oxygen can considerably increase its ability to do so safely by adopting and instituting organizational practices and principles that have been developed and used successfully by others. Likewise, confidence that a project will be successful is much greater if the controls and checks that have been developed through many years of experience are applied in the project management function of the organization.

One purpose of this appendix is to provide an introduction to the general safety-related policies and procedures that are necessary, and beneficial, for an organization that is involved in the use of oxygen so that it can safely accomplish its mission. A second purpose of this appendix is to provide guidance in the safety-related aspects of project management. The policies and procedures and project management guidance given in this appendix may be considered as a safety supplement to the general policies and procedures of an organization and to the general principles of project management, which are not discussed herein except perhaps very briefly. Principles of project management are discussed in numerous sources, such as Refs. [F1] through [F3]. A third purpose of this appendix is to provide a summary of the design, safety, operational, and hazard reviews that are essential for the safe use of oxygen. These reviews provide an assessment of the engineering and safety features of a system design and the operational procedures involved in the use of the system.

System, as referred to in this appendix, could refer to a new site, a new facility at a site, or a new installation at a facility. A general definition is: a group of elements, either people or equipment, that is organized and arranged in such a way that the elements can act as a whole toward achieving some common goal, objective, or end. A system is one of the principal functioning entities comprising the project hardware within a project or program. A system may be considered as the first major subdivision of a project work [F1].

Programs commonly are considered as the necessary first-level elements of a system. A program may be defined as a relative series of undertakings that continue over a period of time (normally years), and is designed to accomplish a broad, scientific or technical goal in a long-range plan [F1]. Projects are also time-phased efforts (much shorter than programs) and are the first level of breakdown of a program. A project may be defined as an effort within a program as an undertaking with a scheduled beginning and end, and which normally involves some primary purpose [F1].

For the purpose of this appendix, there is no basic difference between program management and project management. Thus, the use of project management herein will apply to either as appropriate.

ORGANIZATIONAL POLICIES AND PROCEDURES

An organization involved in the use of oxygen should define, develop, and document necessary policies and procedures (directives) that encompass all phases of a product or system that involves the use of oxygen, from its concept to its removal from service and decommissioning.

One of the responsibilities of senior (top) management of an organization is to establish and enforce policies and procedures by which a project is directed, conducted, controlled, monitored, and evaluated. Senior management of an organization is responsible for providing controls, guidance, and oversight of a project to ensure that proper planning, monitoring, reporting, evaluation, and assessment of the project is achieved.

Policy, as referred to in this appendix, is an organization's plan, or course of action, designed to determine or guide decisions, actions, and other matters within its jurisdiction. It is a course of action, or guiding principle, that is considered to be required, necessary, expedient, prudent, or advantageous.

Procedure, as referred to in this appendix, is an organization's established forms or method for conducting the business of the organization. A procedure provides a manner of proceeding to accomplish a task or goal. A procedure may be composed of a number of steps to define a course of action.

Directive, as referred to in this appendix, is an order or instruction issued by an organization for the purpose of directing how the organization's business will be conducted.

The extent and depth of the application of an organization's policies and procedures should involve consideration of the following:

- the use conditions (especially any extreme conditions of pressure, temperature, and flow),
- the value of the assets (time, property, and personnel) involved,
- the risk to human health and life for employees, customers, and the public, and
- the probability of occurrence and consequence/severity of the hazards involved.

For example, the use of oxygen at high pressure should be of greater concern, and therefore receive more extensive scrutiny, because of the increased concerns and hazards involved.

Designation/Assignment of Authority and Responsibility

An organization involved in the use of oxygen should define, designate, and document the entity that is empowered to implement and enforce the policies and procedures of the organization. The entity with this responsibility is referred to herein as the Authority Having Jurisdiction (AHJ). The AHJ may establish such committees, boards, etc., as required to provide the necessary assistance in accomplishing the mission and responsibility assigned to the AHJ. Examples of such committees and boards include the Design Review Committee and the Materials and Processes Approval Board. The AHJ should ensure that all applicable statutory and regulatory requirements are identified, documented, and adhered to in the use of oxygen. The AHJ may specify that certain voluntary standards be applicable or mandatory for a product or system to be used with oxygen.

The AHJ, as used in this document, is the organization, office, or official responsible for approving equipment, an installation, or a procedure. The designation is used in a broad manner because jurisdiction Ωand approval agencies vary, as do their responsibilities. Where public safety is primary, the AHJ may be a federal, state, local, or other regional department or individual such as a fire chief, fire marshal, labor department official, health department official, building official, electrical inspector, or others having statutory authority. For insurance purposes, the AHJ may be an insurance inspection department, rating bureau, or other insurance company representative. In many circumstances the AHJ is the property owner or his designated agent. At government installations, the AHJ may be the commanding officer or a designated departmental official [F4].

Approved, as used in this document, is defined as being authorized by, or acceptable to, the AHJ. In determining the acceptability of an installation, a procedure, equipment, or materials, the AHJ may base acceptance or compliance on applicable standards and government regulations. In the absence of such standards or government regulations the AHJ may require evidence of proper installation, procedure, or use. The AHJ may also refer to the listings or labeling practices of an organization that is concerned with product evaluations, and that is in a position to determine compliance with appropriate standards and government regulations for the current production of listed items [F4].

Policies and Procedures for Oxygen Use

An organization involved in the use of oxygen should establish, document, implement, and maintain a means of ensuring that the organization's policies and procedures are adhered to; this function is commonly referred to as quality assurance, quality control, quality system, or other similar terms.

An organization involved in the use of oxygen should establish, document, implement, and maintain policies and procedures to:

1. Govern and control all phases of a product or system that involves the use of oxygen, from its concept to its removal from service and decommissioning. Important functions involved in this process include appropriate reviews (such as design reviews) and approvals (such as for the materials and processes used) for a product or system that involves oxygen.
2. Ensure that the specifications and design of a product or system for use with oxygen meet the intended purpose of

the product or system, and that the product or system is safe to use with oxygen.
3. Define and establish a project cycle that is applicable for a product or system that will be used in oxygen service. The project cycle should identify and ensure that pertinent design, materials, and safety reviews are conducted at the appropriate time in the project cycle.
4. Ensure that oxygen is used in a safe manner. Methods that may be used for evaluating the safety of a product or system include a Failure Modes and Effects Analysis (FMEA) and an Oxygen Compatibility Assessment (see Chapter 4). Standard Operating Procedures (SOPs) should be used to direct and control the use of oxygen in a safe manner. All operations should be conducted in accordance with written operating procedures, which are step-by-step checklists, that are approved by the AHJ.
5. Assure that changes in a design, or modification of a product or system, are properly reviewed and approved. The review and approval of a design change, or the modification of a product or system, should involve such reviews and assessments as necessary to ensure that the mission of the product or system is achieved and that this is accomplished in a safe manner.
6. Ensure that periodic (such as annual) reviews are made for operations, training, certification, emergency plans, safety, safety equipment, protective equipment, controls, warning systems, maintenance, hazards, etc.
7. Report, investigate, and document the occurrences, causes, and corrective action required for mishaps, incidents, test failures, accidents, etc.
8. Ensure that its policies and procedures for the use of oxygen are understood, implemented, and maintained at all levels of the organization.

A properly trained workforce that is highly motivated and attentive to working safely is essential in the use of oxygen; consequently, the AHJ should establish policies and procedures to ensure that personnel have proper awareness of oxygen transport, loading, and use operations.

The AHJ should establish policies and procedures for the certification of personnel authorized to handle oxygen or operate systems/facilities that use oxygen. Those who conduct such training must be appropriately certified to provide the training. A person's certification should be renewed periodically.

The AHJ should develop, implement, and maintain a written hazard communications program for the workplace under its jurisdiction in accordance with 29CFR 1910.1200.

Personnel Training, Protection Policies, and Procedures

Consideration for the safety of personnel at and near oxygen storage and use facilities must start in the earliest planning and design stages. Safety documentation should describe the safety organization and comment specifically on inspections, training, safety communications and meetings, operations safety and instruction manuals, accident investigations, and safety instruction records. Training should familiarize personnel with the physical, chemical, and hazardous properties of liquid oxygen (LOX) and gaseous oxygen (GOX), with personal protective equipment, with the correct operation of oxygen systems, and hazard recognition and control.

Equipment failures caused by operator errors can result in fires, explosions, injury, and extensive damage. Operators should be trained for proper operations and be kept informed of any changes in operating or safety procedures. The operators must be qualified and certified for working with GOX and LOX, as appropriate. The operators should also be trained in the corrective actions required in an accident. Personnel engaged in operations should be advised of the hazards that may be encountered.

The AHJ should assure that the safety equipment required for personnel protection at an operational site is present and that all necessary support organizations, such as security, have been notified of operations involving oxygen. Transportation of oxygen-loaded systems should not be scheduled during peak traffic periods if possible, depending on factors such as quantity, risk, and type of system.

Standard Operating Procedures

SOPs, with checklists as required, should be developed for each project. The SOP is a procedure prepared for operation of a system, a facility, or performance of a task on a routine basis. An SOP should be prepared by persons familiar with the work being done and should be reviewed by personnel experienced in oxygen use. SOPs for all hazardous operations should be reviewed by the designated safety authority. Occupational health personnel should be involved in the review cycle when operational procedures involve potential health hazards. The SOPs should be implemented by line management. SOPs should provide for the control of hazards to an acceptable risk and should be reviewed periodically for observance and improvement. The procedures should include:

- notification of the designated safety authority during hazardous operations,
- protection of personnel,
- prevention and detection of oxygen leaks, and
- elimination of ignition sources.

SOPs should be implemented by operating procedures, which are written step-by-step checklists that provide instructions for operating a system, conducting a test, maintenance, etc.

Emergency Plans and Procedures

The AHJ at a facility is responsible for the preparation of emergency plans and implementing emergency procedures. Evacuation routes and requirements and responsibilities of site personnel should be included in these plans. Dry runs of safety procedures should be conducted using both equipment and personnel; periodic safety inspections and surveys should be performed to ensure that emergency procedures are being performed safely. Live exercises should be considered as a means of training and for evaluating emergency plans and procedures.

Quality Control Policy and Procedure

Comprehensive inspection and control are required of all materials and components to be used in GOX and LOX piping installations. A quality control program should be established that will satisfy all requirements established by the AHJ and construction code requirements for all piping, components, materials, and test equipment. Material identification and certification are required for all piping and components used in fabrication and assemblies subjected to GOX and LOX operating conditions. No substitutions for the materials and components specified are permitted, except where the substitution (1) retains oxygen compatibility, (2) maintains compliance with applicable codes and standards, and (3) has written approval of the AHJ.

Required inspections of the piping, storage, and system components should be made according to methods specified by the AHJ. Personnel performing inspections should be appropriately qualified.

PROJECT MANAGEMENT

Successful project management will involve the use of effective planning techniques. This begins with identification of the quantitative and qualitative tools of project planning [F1]. A fundamental tool in this process is the project plan, which involves the various phases of a project.

Project Plan

Regardless of the size of a project, it needs a plan that defines clearly what is to be done, by whom, when, and for how much. The essentials of a project plan include the following:

- a description of the project,
- a list of milestones,
- an activity network that shows the sequence of the elements of the project and how they are related,
- a budget and schedule breakdown for the elements of the project,
- a communication and reporting plan to keep everyone involved in the project informed,
- a description of the review process defining who reviews the project, when, and for what purpose, and
- a list of key project personnel.

Milestones, check points, and reviews are the primary means by which a project is controlled. A detailed discussion of project management and planning is beyond the scope of this appendix. Such is identified as necessary, but the primary focus of this appendix is to provide a review of those safety-related project management and planning methods and techniques that are useful, or required, in a project that involves the use of oxygen. Additionally, some requirements that are unique, or especially important, for the use of oxygen are described in this appendix.

Project Periods and Phases

A project plan should include an identification of the various phases of the project. Every project has certain phases that define its progress and state. As a result of the complex nature and diversity of projects, there is no single definition of the phases of a project. The cycle of a typical project will involve various phases depending upon the particular project and the organization involved. The subject of a project may be a product, a component, a system, a facility, or a combination of these. The typical project cycle represents four basic periods that begin with the identification of a need and progress through concept development, design, hardware, operation (or production), and finally to the stage where the project is ended [F1–F3], that is the:

1. Definition period,
2. Implementation period,
3. Operations period, and,
4. Termination period.

These four project periods may be divided into various project phases for better control and monitoring of a project. A brief description of some typical phases of a project is given below. The various reviews mentioned in these project phases are described in the next section of this appendix.

Definition Period

Phase 1: Identify Need

The project begins with the identification of a need and the decision to address that need. An initial set of requirements and specifications is developed to describe the need. The first phase of a project includes the preliminary evaluation of an idea, and determination of the existing needs, or potential deficiencies, of an existing system that might be available for use in addressing the need.

Phase 2: Develop Concept

In Phase 2, a concept is developed to meet the need that was identified in Phase 1. Tradeoffs for various concepts are evaluated. The requirements and specifications for the project are expanded. Minimum safety requirements are defined. It is essential that the requirements and specifications be as complete (total, comprehensive) and unflawed as possible. The scope of the project is appraised; including requirements such as funding, time frame, manpower, and space (location).

Some efforts involved in the concept phase of a project include the following [F1]:

- establish system concepts that provide initial strategic guidance to overcome existing or potential deficiencies,
- determine initial technical, environmental, and economic feasibility and practicability of the system,
- examine alternative ways of accomplishing the system objectives,
- provide answers to the questions:
  what will the system cost?
  when will the system be available?
  what will the system do?
  how will the system be integrated into existing systems?
- identify the manpower and other resources required to support the system,
- select initial system designs that will satisfy the system objectives,
- determine initial system interfaces, and
- establish a system organization.

An important effort in this phase is a preliminary analysis of risk and the resulting impact on the time, cost, performance requirements, and resources. The concept phase also includes a first cut at the feasibility of a project.

A concept design review (CDR) should be conducted for an early evaluation of the proposed concept. Appropriate safety tasks should be planned and become the foundation for safety efforts during the system design, manufacture, test, and operations. The formal documentation of this is referred to as the system safety program plan (SSPP).

Phase 3: Preliminary Design

In Phase 3, the concept developed in Phase 2 is taken into the design phase. This phase is an expansion and refinement of the elements described in the concept phase. It involves a continued identification of the resources to be required, and an estimate of time, cost, and performance parameters. This phase also includes the initial preparation of all documentation necessary to support the system.

Some efforts involved in this Preliminary Design Phase include the following [F1]:

- initial identification of the manpower and other resources required,

- preparation of the initial system performance requirements,
- preparation of the preliminary plans required to support the system,
- initial estimate of the cost, schedule, and performance requirements,
- identification of those areas of the system where high risk and uncertainty exist, and delineation of plans for further exploration of these areas,
- definition of intersystem and intrasystem interfaces,
- determination of necessary support subsystems, and
- identification and initial preparation of the documents required to support the system, such as policies, procedures, etc.

When the design has progressed sufficiently, a Design Review Team should conduct a preliminary design review (PDR) of the project. The PDR should include an assessment (review) of the materials and processes (M&P) specified for use in the project. A preliminary safety analysis (PSA) should also be made at this time. A preliminary oxygen compatibility assessment (i.e., POCA) and a FMEA also may be made at this time to identify the hazards involved in the project and the manner in which these hazards are addressed. Changes to the design may be recommended as a result of these preliminary reviews and assessments. The design, the design review, and the safety analysis should be considered preliminary until they are finalized.

Phase 4: Final Design

In Phase 4, the design is continued, guided by the reviews that were made in Phase 3. Details of the design are completed. This phase of a project is a detailing, refinement, and finalization of the elements described in the preliminary design phase. The final design phase requires a firm identification of the resources to be required, and a firm establishment of realistic time, cost, and performance parameters. This phase also includes a finalization of the preparation of all documentation necessary to support the system.

Some efforts involved in the final design phase of a project include the following [F1]:

- the firm identification of the manpower and other resources required,
- preparation of the final system performance requirements,
- preparation of the detailed plans required to support the system,
- determination of realistic cost, schedule, and performance requirements, and
- preparation of the documents required to support the system, such as policies, procedures, etc.

Upon completion of the design, a design review team should conduct a final design review (FDR), or critical design review, of the project. A final safety analysis (FSA) and an FMEA should be completed for the project. The subsystem and system Final Oxygen Compatibility Assessments (FOCA) should be completed and close-out actions should be completed prior to proceeding with the Fabrication and Construction Phase.

Changes to the design may be recommended as a result of these final reviews and assessments. Another iteration of the FDR, FSA, FMEA, and final oxygen compatability time FOCA may be necessary depending on the extent of any revisions made in the design. The Final Design Phase is completed by a design certification review (DCR).

Implementation Period

Phase 5: Fabrication and Construction

In Phase 5, the project moves from paper to hardware. Phase 5 of a project is predominantly a fabrication and construction effort. The parts, pieces, components, and subsystems of the project are procured, fabricated, or constructed in this phase. Preparations for the Commissioning Phase should begin, if not already in progress.

Some efforts involved in this phase of a project include the following [F1]:

- updating of detailed plans conceived and defined during the preceding phases,
- identification and management of the resources required to facilitate the fabrication/construction processes, and
- verification of system installation specifications.

Phase 6: Installation

The components and equipment are installed in this phase. Almost all documentation must be completed in this phase. Some efforts involved in the installation phase of a project include the following [F1]:

- finalization of plans for checkout and acceptance testing to determine adequacy of the system to do the things that it is intended to do,
- preparation for the operational readiness review (ORR),
- preparation for the emergency procedures review,
- finalization of technical manuals and affiliated documentation describing how the system is intended to operate, and
- development of plans to support the system during its operational phase.

Phase 7: Commissioning

As the installation progresses, the checkouts of the components and subsystems of the project are made. Eventually the installation of the system or facility is completed, a checkout of the complete system is conducted, and Acceptance Testing is completed. The Commissioning Phase consists of such checks and tests that verify that the system is functioning as designed and is ready for the Operation Phase; thus this phase is predominantly a testing effort so that operations can begin.

Some efforts involved in this phase of a project include the following [F1]:

- updating of detailed plans conceived and defined during the preceding phases,
- identification and management of the resources required to facilitate the operational phase,
- verification of system specifications,
- performance of final testing to determine adequacy of the system to do the things that it is intended to do,
- development of technical manuals and affiliated documentation describing how the system is intended to operate, and
- finalizing development of plans to support the system during its operational phase.

Almost all documentation must be completed in this phase, including flow schematics, pressure vessel certification, cleaning certification, and specifications for components used.

The intent of checkout tests of components, subsystems, and the complete system is to ensure their integrity and suitability for its intended use. A wide variety of tests may be required, depending upon the critical nature of the equipment. Compliance with approved requirements of the AHJ is essential for these tests. Initial testing, such as leak testing, is often best performed with inert fluids; however, acceptance tests of the final hardware configuration should be conducted with clean oxygen and parts cleaned for oxygen service. Testing with oxygen must begin only after an oxygen compatibility assessment has been performed on the specific test hardware. Remote operation with only essential personnel present should be considered for initial testing. The checkout and testing of a system may involve a variety of tests that may include the following:

Development Testing
This testing is intended to verify safe and reliable operation over a realistic range of operating conditions. It includes pressure integrity tests, assembly leak tests, and configurational tests.

Worst-Case Operating Condition Testing
Testing at worst-case conditions should be considered to evaluate limited design margins, single-point failures, and any uncertainties in the design criteria. Life-cycle and flow tests are important in this phase of testing. Life-cycle tests should be performed to determine the safety and longevity of system components. The components should be tested in each operational mode with the number of cycles based on the anticipated end-use.

Oxygen Compatibility Testing
Testing should also be conducted to ensure compatibility of the component and system with oxygen in its intended operation. Experience indicates that 60 cycles for each of two configurations or 30 cycles for each of four configurations will verify the functionality of components designed for oxygen service. These do not constitute qualification, life-cycle, or pressure qualification (proof) tests.

Qualification Testing
Qualification testing should be performed on components, systems, or both to verify that they meet specification requirements and to identify defects that may exist in the component or system. This testing should focus on the ignition mechanisms identified in the Oxygen Compatibility Assessment.

Acceptance Testing
The acceptance test is a standard test that leads to certification of a component or system. The acceptance test is the final test, or series of tests, conducted to ensure that the system, or facility, meets the performance specifications.

Checkout Testing
Checkout tests should include verification of proper operation of all controls and instrumentation, including computer and computer software that is used for system control and monitoring.

A test readiness review (TRR) should be conducted before any test involving oxygen, or any operation that involves a hazardous condition, to verify that all of the necessary preparations for the test have been completed. The safety analysis report (SAR) should be completed and certify that all safety requirements have been met and that any recommended or required actions have been addressed satisfactorily. The materials compatibility assessment should be completed and any concerns that were identified should be satisfactorily addressed.

The SOPs and associated operating procedures should be completed and approved. The Operator Training Review and operating procedures review (OPR) should be completed and approved. An emergency procedures review (EPR) should be conducted before the start of operations with oxygen.

The final step in the commissioning phase is the ORR. An ORR should be conducted prior to the start of operation of a system. However, an ORR may be required before a system is exposed to oxygen for the first time such as might occur during the tests involved in the commissioning phase.

Operations Period

Phase 8: Operation
The eighth phase is the operation phase. During this phase the project's product or service is integrated into the existing organization.

Some efforts involved in the operations phase of a project include the following [F1]:

- use of the system, and the results obtained, by the intended user or customer,
- actual integration of the project's product or service into existing organizational systems,
- evaluation of the technical, social, and economic sufficiency of the project to meet actual operating conditions,
- routine maintenance of components such as filters, gages, and relief devices,
- assessment of debris removed from filters,
- periodic pressure testing (recertification) of pressure vessels,
- provision of feedback to organizational planners concerned with developing new projects and systems, and
- evaluation of the adequacy of supporting systems.

Problem reporting is very important during the Operation Phase. Proper handling of problems can lead to learning, repairs, and avoiding failures. Safety Assessment Reviews (SAsR) should be made at periodic intervals during operation of the system to verify that the system remains safe for operation. The SAsR may include updating of other reviews and analyses, such as the oxygen compatibility assessment. A TRR should be conducted for tests that involve test conditions or procedures that were not addressed in a previous TRR.

Termination Period

Phase 9: Removal from Service
After the system has completed its mission, it should be removed from service and made safe. It may be maintained in a state wherein it could be reactivated for a future need. An approved plan should be followed in removing a system from service and in any reactivation effort. This phase of a project includes shutting down the system and the reallocation of resources. The efforts on the total system are evaluated in this phase, and the results serve as input to the Concept Phase for new projects and systems.

Some efforts involved in this phase of a project include the following [F1]:

- system phase-down,
- development of plans transferring responsibility to supporting organizations,
- divestment or transfer of resources to other systems,
- development of "lessons learned from system" for inclusion in qualitative-quantitative data base to include: assessment of performance,

major problems encountered and their solution,
technological advances,
advancements in knowledge relative to the organization's strategic objectives,
new or improved management techniques,
recommendations for future research and development,
recommendations for the management of future programs, and
other major lessons learned during the course of the system.

Phase 10: Decommission and Disposal

Eventually, the system will be deactivated, torn down, and scraped or disposed of in an approved manner.

DESIGN REVIEWS, SAFETY REVIEWS, OPERATIONAL REVIEWS, HAZARD REVIEWS, AND COMPATIBILITY ASSESSMENTS

Various reviews should be made of a system before its being used with oxygen. Also, various reviews should be conducted regularly as part of an ongoing program to ensure a continual safe use of oxygen,. A review consists of a careful and critical examination, analysis, and evaluation of a system; some reviews may be specific (safety, for example) whereas others may be more general and cover several, or all, aspects of a system and its operation.

The reviews discussed here are necessary regardless of the size of a project, or system. The reviews may require multiple people and days to accomplish. Regardless of the number of people involved and the time required to accomplish these reviews, a formal documentation of the results of the reviews should be made.

Design Reviews

The design review is a formal, documented, review of a product or system design and is conducted by a team of people of various pertinent fields of expertise that covers the technical and administrative aspects and all phases of the project. Tradeoffs that involve technical requirements, safety, time, cost, etc., (some of these may be conflicting factors) must be evaluated and judgments made. The experience and technical capability of the members of the design review team will be especially important in the assessment of tradeoffs and in the resolution of conflicting factors.

Consideration should be given in the design review and oxygen compatibility assessment for the shutdown of transfer systems, for the automatic closing of special lines and systems, and for the use of isolation valves in various legs of multiple systems.

In addition to the standard practice of reviewing functional operation, component ignition and combustion in oxygen-enriched environments must also be assessed. The overall design process must reduce the hazards associated with component ignition and combustion. Before constructing oxygen systems, the design safety should be approved by the AHJ. The design review process should be conducted in accordance with the approved procedures of the AHJ.

Reviews of the final drawings, designs, structures, and flow and containment systems should include a safety assessment to identify potential system hazards and compliance with local, state, and federal agency regulations. The safety assessment should also include the safety history of the system hardware. Such histories can identify equipment failures that may create hazardous conditions when the equipment is integrated.

The safety assessment process should be integrated into the overall facility design review process. Each design review phase should evaluate the safety aspects of the project according to its level of completion.

All the procedures described in this section refer to the design of both components and systems for oxygen use. The design reviews ultimately need to address all design aspects down to the individual part level, because all parts pose potential hazards in oxygen service.

Concept Design Review (CDR)

A CDR is used to establish that the purpose and design performance criteria that have been developed for a system will produce a system that will meet the need for which it is intended. A CDR may be conducted when the proposed and selected design approaches and basic technologies have been delineated sufficiently to indicate the type and magnitude of the principal potential hazards. The CDR should show that applicable design codes, safety factors, and safety criteria have been specified, and that a PHA has been started. The CDR occurs when the design is approximately 10 % completed.

Preliminary Design Review (PDR)

A PDR should be conducted when the design is about 50 % completed. The PDR should contain the stress calculations for critical structures and show that design codes, safety factors, and safety criteria have been met. The PDR should include materials and specifications reviews. The PHA should be completed and system/subsystem hazards analyses should be under way.

Final Design Review (FDR)

A FDR (this may also be known as a critical design review) should be conducted when the design is about 90 % completed. The final design review should be held after all preliminary analyses have been completed and the action items from these analyses have been resolved. In this review, the final fabrication drawings and the supporting calculations should be reviewed and all final action items resolved before authorizing fabrication and use.

The FDR should contain a review of the design to show that conformance to design codes, required safety factors, and other safety criteria have been achieved. Proposed construction methods and arrangements should make clear that construction hazards will be effectively controlled. Procurement documents, such as a statement of work (SOW), should specify appropriate safety requirements.

The FDR of the final drawings, designs, structures, and flow and containment systems should include appropriate safety reviews. The design and safety reviews should identify areas of requirements and compliance therewith as required by local, state, and federal agencies.

Design Certification Review (DCR)

A DCR should be conducted when the design is 100 % complete to show that all project documentation (drawings, SOW, specifications) are completed, reviewed, and approved. All hazards analyses should be complete, including close-out actions. Actions from previous design and safety reviews should be verified as complete.

Safety Reviews

At each phase in a system, specific safety tasks should be accomplished to ensure safety during construction, operation, maintenance, and final disposition of the system. These safety tasks should be tailored to include the appropriate tasks considering the size and complexity of the system and the associated safety risks and consequences of a mishap or failure. The application of these requirements should be considered for the modification or reactivation of an existing system.

Safety Analysis

All safety aspects, including oxygen hazards, should be reviewed to ensure that the integrated design solution does not present unacceptable risks to personnel and property in accordance with approved requirements of the AHJ.

A safety analysis should be made for a system or facility before its becoming operational for using oxygen. A system should be evaluated for potential risks to the operators, the public, and the environment. The AHJ should determine the level of the safety analysis based on the facility functions and potential accident risk. The PSA should be initiated during the Preliminary Design phase and the results included in the PDR. The FSA should begin after completion of the final design phase, and should be completed and approved prior to start of operations. The safety analysis should address items such as the following:

- form, type, and amount of oxygen and other hazardous materials to be stored, handled, or processed;
- principal design, construction, and operating features selected for preventing accidents or reducing risks to acceptable levels, including the safety margins used.
- principal hazards and risks that can be encountered in system or facility operation, including potential accidents and predicted consequences of events such as fire, explosion, structural failure, wind, flood, lightning, earthquake, tornado, operating error, failure of essential operating equipment, and failure of safety systems;
- materials (both metallic and nonmetallic) used;
- cleaning levels;
- pressure relief protection;
- pressurization and flow rates; and
- the design basis accidents that were postulated and quantified, including the rationale for their selection. A design basis accident is a postulated accident and resulting conditions for which the confinement structures, systems, and components must meet their functional goals.

Safety Analysis Report (SAR)

The results of the PSA and the FSA should be documented in a SAR. The SAR is a report of the formal evaluation that was made to:

1. Systematically identify the hazards involved in a system/facility/operation,
2. Describe and analyze the adequacy of the measures taken to eliminate, control, or mitigate identified hazards, and
3. Analyze and evaluate potential accidents and their associated risks.

The SAR will address in considerable detail all of the significant safety, health, and environmental, aspects of a system and its operation.

System Safety Program Plan (SSPP)

A SSPP should be prepared. The SSPP is a description of the methods to be used to implement the tailored requirements of a standard, including organizational responsibilities, resources, methods of accomplishment, milestones, depth of effort, and integration with other program engineering and management activities and related systems.

Safety Assessment Review (SAsR)

A SAsR should be made for a new system and should be updated anytime a system or process is changed. A periodic system inspection should be conducted and documented.

Failure Modes and Effects Analysis (FMEA)

The FMEA is a risk analysis technique or procedure. It is a formal, documented, design evaluation procedure that is used to identify all conceivable and potential failure modes and to determine the effect of each failure mode on system performance. This procedure consists of a sequence of logical steps, starting with the analysis of lower-level components or subsystems. The analysis assumes a failure point of view and identifies all potential modes of failure along with the cause (the "failure mechanism"). The effect of each failure mode is then traced up to the systems level. A criticality rating is developed for each failure mode and resulting effect. The rating is based on the probability of occurrence, severity, and detectability. Design changes are recommended to reduce criticality for failures scoring a high rating.

The FMEA is used to review each hardware item and analyzes it for each possible single-point failure mode and single-barrier failure and their worst-case effects on the entire system. An FMEA also will include the results of the oxygen compatibility assessment.

The interdependencies of all components must be addressed, and any single-point failure and the result of any single-barrier failure must be noted in a summary list of action items to be corrected. Single-barrier failures are often overlooked, but the potential for component-part failures, such as diaphragm failures, can cause hazardous oxygen-enriched environments, and can cause a substantially increased risk of ignition near electrical components, for example.

Attempting to correct single-point failures simply through procedural actions is not an acceptable technique to achieve a safe design. That is, relying on adherence to an operating procedure to maintain a safe condition in the situation where the failure of a single component can cause an undesired event is not an acceptable solution to this undesirable feature.

The FMEA should consider the effects of failures in both static and dynamic operating conditions. When performed early in the design phase, the FMEA greatly assists the designer in ensuring reliable systems. Finally, the FMEA should be performed before fabrication of the component or system.

Material Compatibility Assessment

The logic for determining whether or not a material can be used safely in oxygen service is shown in Fig. 4-3 of Chapter 4. Potential ignition sources should be evaluated to ensure no special hazards exist. Potential ignition sources should be eliminated through engineering design wherever feasible. If an ignition source exists, configurational and component tests should be performed to determine the safety margins to the ignition thresholds of the material. Chapters 2 and 3 give more information on ignition sources and test methods.

Operational Reviews

Operating Procedures Review

Operational procedures, along with instrumentation and control systems, should be evaluated for their capacity to provide the required safety. Equipment performance should be verified by analysis or certification testing. It may be necessary to develop special procedures to counter hazardous conditions. Periodic OPR should be made.

Operator Training Review

Operator training should be reviewed and demonstrated to be adequate before operations commence. Operator training should be evaluated continuously.

Test Readiness Review (TRR)

A TRR should be conducted before any test involving oxygen or before any operation that involves a hazardous condition to verify that all of the necessary preparations for the test have been completed.

Operational procedures, along with instrumentation and control systems, should be evaluated during the TRR for their capacity to provide the required safety. Equipment performance should be verified by analysis or by certification testing. It may be necessary to develop special procedures to counter hazardous conditions.

Operational Readiness Inspection (ORI)

In addition to the design, safety, and compatibility assessments mentioned in this appendix, an ORI may be required before a system is activated. The ORI is a formal review of a system that is undergoing initial activation or major modifications. The purpose of the ORI is to ensure that proper standards of safety and operational readiness are achieved prior to commitment of the system and to ensure that programs have been devised and implemented that will systematically maintain the safety and operational posture of all anticipated future operations.

An ORI may be required for any major change in equipment or the system. Oxygen compatibility should be reviewed specifically for compliance with approved requirements of the AHJ. The ORI should be conducted prior to the TRR.

Operational Readiness Review (ORR)

An ORR should be conducted before the start of operation of a system. An ORR may be required for any major system change.

Emergency Procedures Review (EPR)

The safety of personnel at and near an oxygen system or facility should be carefully reviewed and emergency procedures developed at the earliest planning and design stages. Advance planning for a variety of emergencies such as fires and explosions should be undertaken so the first priority is the reduction of risk to life. Periodic EPRs should be made.

Hazard Reviews

The use of oxygen involves a degree of risk that must never be overlooked. A hazard analysis should be performed on any component or system intended for oxygen service. The hazard analysis should include reviews of the system design, component design, operating procedures (emphasizing those that increase the probability of personnel exposure), maintenance procedures, protective measures, in-service inspection requirements, and emergency procedures. The hazard analysis should identify static and operational hazards and provide information for developing safer and more reliable components and systems. The hazard analysis allows a better understanding of the basis for the safety requirements and emphasizes the need for compliance with established regulations.

The hazard analysis, performed both at the component and system level, shall be integrated with the FMEA and shall identify any condition that could possibly cause leakage, fire, explosion, injury, death, or damage to the system or surrounding property (*ASTM Standard Guide for Designing Systems for Oxygen Service G 88*). It should also:

- include the effects of component and assembly single-point failures;
- review all ignition modes for all components and assemblies;
- include hazards associated with contamination;
- review secondary hazards, such as seal leakage to electrical equipment;
- consider the effects of maintenance procedures on safety and performance; and
- review toxicity concerns, especially for breathing oxygen.

The hazard analysis should be conducted according to the following outline:

1. Determine the most severe operating conditions.
2. Evaluate flammability of materials at the use conditions (situational flammability).
3. Evaluate ignition sources.
4. Compare the above existing data and perform configurational and component tests if required to determine and demonstrate safety margins to ignition thresholds.

The hazard analysis shall consider the most severe operating conditions, and their effects upon the system. It shall include the effect of operational anomalies and single-point failure modes, such as ignition, combustion, explosion, or the effect of oxygen enrichment of a normally ambient environment.

The following parameters define some of the operating conditions relevant to the hazards of an oxygen system:

- temperature,
- pressure,
- oxygen concentration,
- flow velocity,
- rubbing parameters (load, speed), and
- multiple duty cycles.

Components must be evaluated at the worst conditions they would experience given a single-point failure in the system. If it cannot be determined which condition is most severe or if the trends in material ignition and flammability (as a function of the parameters listed previously) are not understood, then the range of operating conditions must be considered.

Methods of performing a hazard analysis include techniques such as fault hazard analysis and fault-tree analysis, in which undesirable events are evaluated and displayed, or a failure mode and effects analysis and single-barrier failure analysis, in which potential failures and the resulting effects (to include ignition and combustion in oxygen-enriched atmospheres) on the safety of the system is evaluated.

Hazard and operational analyses shall be continued during operations and testing. This hazard analysis shall identify all of the hazards associated with the system or operations from the beginning of oxygen use to the disposal of the oxygen system.

A formal operating and support hazard analysis shall be performed as directed by the authority having jurisdiction. Significant hazards identified shall be eliminated or reduced to acceptable risk levels. A record of inspections and operating and support hazard analyses shall be retained on file at the involved installation for a minimum of 4 years.

Compatibility Assessment

An oxygen compatibility assessment should be performed on any component or system intended for oxygen service, preferably prior to system buildup. This assessment should include reviews of the system design, component design, operating procedures (emphasizing those that increase the probability of personnel exposure), maintenance procedures, protective measures, in-service inspection requirements, and emergency procedures. A detailed description of the compatibility assessment process is given in Chapter 4. The compatibility assessment should be integrated with the FMEA and should identify any condition that could possibly cause leakage, fire, explosion, injury, death, or damage to the system or surrounding property (*ASTM Standard Guide for Designing Systems for Oxygen Service G 88*).

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[F1] Kerzner, H., *Project Management—A Systems Approach to Planning, Scheduling, and Controlling*, Second Edition, Van Nostrand Reinhold Co., New York, 1984.

[F2] Cleland, D. I., ed., *Field Guide to Project Management*, Van Nostrand Reinhold Co., New York, 1998.

[F3] Forsberg, K., Mooz, H. and Cotterman, H., *Visualizing Project Management*, New York, Wiley, 1996.

[F4] NFPA 50, *Standard for Bulk Oxygen Systems at Consumer Sites*, National Fire Protection Association, Quincy, MA, 1996.

APPENDIX G

Glossary

Acceptance testing, limited production testing that is designed to verify that products, which have been qualified to meet design specifications, conform to specification requirements. Acceptance tests are generally less comprehensive than Qualification tests and are nondestructive in nature.

Adiabatic, a process by which the system changes state without thermal energy exchange between the system and the surroundings.

Adiabatic compression, mechanical work transferred to a system, where the energy goes into increasing the internal energy of the material for a static system or increasing the enthalpy for a dynamic system. If the process is also reversible (in the thermodynamic definition), this change is also isentropic.

Ambient, may refer to the international standard atmospheric conditions at sea level [288 K (59°F) temperature and 101.325 kPa (14.696 psi) absolute pressure] or it may refer to the local temperature and pressure of a particular location, such as a city or a facility.

Autogenous ignition (autoignition) temperature (AIT), the lowest temperature at which material will spontaneously ignite (autogenous ignition).

Autoignition, the phenomenon in which a mixture of gases, vapors, mists, dusts, or sprays ignites spontaneously with no external ignition source. It is frequently called "autogenous ignition" or "spontaneous ignition."

Blast wave, a shock wave in air, which has degenerated as the shock front becomes less dense.

Blast yield, energy released in an explosion, inferred from measurements of the characteristics of the blast waves generated by the explosion.

Buddy system, a system used in hazardous operations where one person performs the necessary task while another person standing nearby is fully prepared (clothing, training, etc.) to remove the primary person from the area in case of incapacitation.

Cargo tank, any container designed to be permanently attached to any motor vehicle or other highway vehicle and in which any compressed gas is to be transported. The term "cargo tank" does not include any tank used solely to supply fuel for the vehicle or containers fabricated for cylinders.

Certification, the process that results in the documented status that qualifies a vessel or system to operate in the service for which it is intended or qualifies operating personnel for specific duties. Also refers to the document itself.

Cleanliness level, an established maximum of allowable contaminants based on sized distribution, or quantity on a given area or in a specific volume. Also, an absence of particulate and nonparticulate matter visible under visible light or UV illumination or both.

Cold injury, an injury caused by freezing of skin tissue caused by exposure to a very cold atmosphere, surface, or cryogen. Also referred to as a "cryogenic burn."

Combustible liquid, a liquid with a flash point at or above 333 K (140°F).

Combustible solid, a solid that can burn in the presence of an oxidizer.

Confined space, a space not normally occupied by personnel. It has limited or restricted openings for entry and exit, may lack adequate ventilation, and may contain or produce "dangerous air contamination;" therefore, it may not be safe for entry.

Contaminant, a foreign substance that can have deleterious effects on system operation, life, or reliability.

Critical surface, a surface that requires precision cleaning.

Cryogen, substances that boil at extremely low temperatures, usually at or below 123 K (−238°F).

Explosion, the rapid equilibration of pressure between the system and the surroundings. The pressure of the gas is dissipated as a shock wave. Explosions may occur through mechanical failure of vessels containing high-pressure fluids or through rapid chemical reactions producing large volumes of hot gases.

Explosive, any chemical compound or mechanical mixture that when ignited, undergoes a very rapid combustion or decomposition releasing large volumes of heated gases that exert pressure on the surrounding medium.

Fire resistant, materials that will resist burning when contacted by fuels or oxidizers, but will eventually burn after continuous contact and exposure to an ignition source.

Flammable, capable of being ignited and burned.

Flammable liquid, any liquid with a flash point below 300 K (80°F) as determined by standard methods (ASTM D 56; ASTM D 92).

Flash point, the lowest temperature, corrected to an absolute pressure of 101.325 kPa (14.696 psi), at which an ignition source under specified conditions, causes the material vapor to ignite momentarily.

Fragmentation, the breaking up of the confining material when an explosion takes place. Fragments may be complete items, subassemblies, pieces of material, or pieces of equipment or buildings containing the flame.

Geysering, occurs in vertical systems with a tank and a long feedline from the tank filled with cryogenic oxygen. Heat transfer into the line causes gas bubbles to form and begin rising in the line. As the bubbles rise, they coalesce to form larger bubbles. In a line long with respect to its diameter, the result is an expanding vapor bubble of sufficient size to expel the liquid above it into the tank with a force large enough at times to rupture the tank or to damage internal tank components such as baffles, screens, or level sensors. When the liquid subsequently reenters the line, it can cause large water hammer forces with accompanying system damage.

Glass transition temperature (T_g), that temperature at which, upon cooling, a noncrystalline polymer transforms from a supercooled liquid to a rigid glass.

Hazard, existing or potential condition that can result in or contribute to a mishap.

Hazards analysis, a process that analyzes all possible ignition sources and the flammability of all materials present.

Heat of combustion, the difference in the enthalpy of the products and the enthalpy of reactants for a given temperature and pressure.

High pressure, pressure greater than or equal to 1 MPa (150 psi).

Hydrostatic test, a test performed on a pressure vessel or system in which the vessel or system is filled with a liquid (usually water) and pressurized to a designated level as prescribed in the applicable code.

Ignition energy, the energy required to initiate flame propagation through a flammable mixture. The minimum ignition energy is the minimum energy required to ignite a particular flammable mixture at a specified temperature and pressure.

Ignition temperature, the temperature required to ignite a substance.

Material certification, a document from a manufacturer or supplier that specifies that a material is indeed what the manufacturer claims it to be.

Maximum allowable working pressure (MAWP), the maximum allowable operating pressure rating of pressure vessels manufactured and operated in accordance with ASME Boiler and Pressure Vessel Code.

Noncombustible, a material (as defined in NFPA 220), which, in the form and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat. Materials reported as noncombustible, when tested in accordance with ASTM E 136–79, shall be considered noncombustible materials.

Nonmetal, any material not containing metal, such as polymers. However, for the purposes of this document, "nonmetal" does not include ceramics, although they are classified as nonmetals.

Normal boiling point (NBP) for oxygen, NBP = 90 K = −183°C = −297°F at a pressure of 101.325 kPa (14.696 psi) absolute.

Normal temperature and pressure (NTP), 293.15 K (68°F) and 101.325 kPa (14.696 psi).

Operating pressure, the pressure of a vessel at which it normally operates. This pressure must not exceed the maximum allowable working pressure.

Operating temperature, the temperature maintained in the part under consideration during normal operation.

Overpressure, a blast wave above the ambient atmospheric pressure resulting from an explosion or pressure in a component or system that exceeds the MAWP or other defined maximum pressure of the component or system.

Oxygen-enriched, several definitions of oxygen enrichment are found in the literature. Oxygen-enriched atmospheres have been specified for oxygen concentrations greater than 21 vol% (NFPA 53), 23.5 vol% (29 CFR 1910.146), and 25 vol% or an absolute partial pressure of oxygen equal to or greater than 25.3 kPa (3.7 psi) under ambient pressure (ASTM G 63–92). Oxygen-enriched atmospheres expand the range of flammability, lower the ignition energy, and cause combustible materials to burn violently when ignited.

Oxygen index, minimum concentration of oxygen in an ascending flow of oxygen and nitrogen at one atmosphere pressure that will just sustain combustion of a top-ignited, vertical test specimen (ASTM D 2863).

Particulate, a finely divided solid of organic or inorganic matter, including metals. These solids are usually reported as the amount of contaminant, by the number of a specific micrometer size present.

Pilling and Bedworth ratio, a criteria for establishing whether an oxide is protective. It is based upon whether the oxide that grows on a metal occupies a volume greater or less than the volume of the metal that it replaces. The Pilling and Bedworth ratio recommended by the ASTM Committee G-4 is: Pilling and Bedworth ratio = Wd/awD, where the metal, M, forms the oxide, M_aO_b; a and b are the oxide stoichiometry coefficients; W is the formula weight of the oxide; d is the density of the metal; w is the formula weight of the metal; and D is the density of the oxide.

Portable tanks, any tank or container as defined by the DOT, designed primarily to be temporarily attached to a motor vehicle, other vehicle, railroad car other than tank car, or marine vessel, and equipped with skids, mountings, or accessories to facilitate mechanical handling of the container, in which any compressed gas is to be transported in.

Precision cleaning, final or fine cleaning accomplished in a controlled environment to achieve some cleanliness level.

Precision cleanliness, a degree of cleanliness that requires special equipment and techniques for determination. Precision cleanliness levels normally include limits for particulate size and quantities.

Precleaning, all cleaning activities and procedures required to prepare items for precision cleaning.

Pressure vessel, any certified vessel used for the storage or handling of gas or liquid under positive pressure.

Promoters, devices such as igniters, which by burning are intended to cause ignition of an adjacent surface.

Proof test, a pressure test performed to establish the maximum allowable working pressure of a vessel, system, or component thereof: (1) when the strength cannot be computed with satisfactory accuracy; (2) when the thickness cannot be determined by means of the design rule of the applicable code or standard; or (3) when the critical flaw size to cause failure at the certified pressure cannot be identified by other nondestructive test methods.

Propellant, fuels and oxidizers used in jet and rocket engines. When ignited in a combustion chamber, the propellants change into gases with a large increase in pressure, thus providing the energy for thrust.

***Pv* product**, a measure of the relative resistance to ignition by friction. It is the product required for ignition (where P is the normal load divided by the initial contact area and v is the relative linear velocity between the samples). Determined by a frictional heating test. Additional detail is provided in Chapter 3.

Pyrolysis, the chemical decomposition of a material by thermal energy.

Qualification testing, comprehensive tests that are designed to demonstrate that a product meets its specified requirements before it is released for production. Qualification tests may include tests to destruction.

Radiant heat, heat that requires no medium to travel through, unlike conduction (direct and contact) or convection (transport of heat by fluid movement).

Recertification, the procedure by which a previously certified vessel or system, by appropriate tests, inspections, examinations, and documentation, is qualified to continue or be returned to operations at the designed pressure.

Risk, the likelihood of occurrence of a specific consequence or loss, caused by faults or failures, or external events. For example, the number of fatalities deriving from possible failures in a given hazardous activity is the risk. When qualified, risk is often also used to mean the product of the likelihood, expressed as a probability, and the magnitude of a given loss, or the sum of such products over all possible losses, in other words, the expected loss. Individual risk is the probability of a given consequence (such as a fatality) occurring to any member of the exposed population. Group or social risk is the probability that a given number of individuals will suffer a given consequence.

Safety factor, the ratio, allowed for in design, between the ultimate breaking strength of a member, material, structure, or equipment and the actual working stress or safe permissible load placed on it during ordinary use.

Set pressure, the pressure marked on a safety relief valve at which system pressure relief begins.

Shock sensitivity, the ease with which a material may be ignited by a mechanical impact, producing a deflagration or detonation.

Single-barrier failure, a system or design in which the failure of a single barrier, which may be a physical, electronic entity, or computer code, to perform as intended causes the entire system or design to function unpredictably or catastrophically.

Single-fault tolerant, a system or design in which the failure of a single element to perform, as intended, does not cause the entire system or design to function unpredictably or catastrophically; that is, it will continue to function as intended.

Single-point failure, a system or design in which the failure of a single element to perform as intended causes the entire system or design to function unpredictably or catastrophically.

Situationally flammable, a material that is flammable in oxygen in the use configuration and conditions (for example, temperature and pressure).

Standard temperature and pressure (STP), 273.15 K (32 °F) and 101.325 kPa (14.696 psi).

Storage container, any container designed to be permanently mounted on a stationary foundation and used to store any compressed gas.

System safety program plan (SSPP), a description of the methods to be used to implement the tailored requirements of a standard, including organizational responsibilities, resources, methods of accomplishment, milestones, depth of effort, and integration with other program engineering and management activities and related systems.

Tank, any vessel used for the storage or handling of liquids where the internal pressure depends only on liquid head or a combination of liquid head and vapor pressure.

Two-fault tolerant, a system or design in which the failure of two elements does not cause the entire system or design to function unpredictably or catastrophically; that is, it will continue to function as intended. The faults may be in related areas or function completely independently.

Two-point (double-point) failure, a system or design in which the failure of two elements causes the entire system or design to function unpredictably or catastrophically. The system or design is essentially single-fault tolerant.

Erratum for ASTM Safe Use of Oxygen and Oxygen Systems: Handbook for Design, Operation, and Maintenance 2nd Edition, published October 2007.

CORRECTION:

Page 110, TableB-4 – Thermal properties of selected materials at room temperature, LOX temperature, and liquid hydrogen temperature.

Entries for 304 and 304L are:

Stainless steels					
304	300	14.7[d]	500[j]	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	8.6[d]	12.7[d]	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	2.12[d]	...	0.5×10^{-6} [d]	-298×10^{-5} [d]
304L	300	14.7[d]	...	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	8.6[d]	11.8[d]	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	2.12[d]	...	0.5×10^{-6} [d]	-298×10^{-5} [d]

Entries should read:

Stainless steels					
304	300	14.7[d]	500[j]	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	8.6[d]	...*	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	2.12[d]	12.7[d]*	0.5×10^{-6} [d]	-298×10^{-5} [d]
304L	300	14.7[d]	...	15.9×10^{-6} [d]	$+12 \times 10^{-5}$ [d]
	90	8.6[d]	...*	8.3×10^{-6} [d]	-269×10^{-5} [d]
	20	2.12[d]	11.8[d]*	0.5×10^{-6} [d]	-298×10^{-5} [d]

* These data points have been corrected since the initial printing.